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Carbon sequestration of two oil mallee species, eucalyptus loxophleba subsp. lissophloia and eucalyptus. kochii subsp. plenissima in the semi-arid environment of the Central Wheatbelt of Western Australia

Andrew Phillip McCarthy

CARBON SEQUESTRATION

OF TWO "OIL MALLEE" SPECIES,

Eucalyptus loxophleba subsp. *lissophloia*

and

Eucalyptus. kochii subsp. *plenissima*

IN THE SEMI-ARID ENVIRONMENT OF THE CENTRAL WHEATBELT OF WESTERN AUSTRALIA

An Honours Thesis presented for a Bachelor of Science (Honours)

By: ANDREW PHILLIP McCARTHY

Edith Cowan University

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

ABSTRACT

The planting of "Oil mallees" have a number of implications in terms of environmental management within Western Australia. Firstly, the incorporation of perennial trees on a large scale into the agricultural landscape can assist in balancing the hydrological cycle and other land degradation problems (Bird *et. al.* 1992; Western Australian Salinity Action Plan, 1996). Secondly, harvesting the above-ground biomass can produce an economic return because of the oil contained within the leaves. This oil has the potential to replace ozone damaging solvents (Barton and Knight, 1997;Wildy, 1996). Finally, "oil mallees" have the potential to offset greenhouse gas emissions, because mallee Eucalypts have a sizeable carbon sink, in the form of a root system that continues to grow after harvesting the above-ground growth (James, 1984). These sinks can potentially be traded, providing the landowner with another income source. For "oil mallees" to realise the potential outlined above, there is a need to obtain information on their growth characteristics, particularly that of the below-ground structures

The aims of the research presented in this thesis were to determine the biomass and amount of carbon being sequested by the below ground organs of *E. kochii* subsp. *plenissima* at four different ages, and of *E. loxophleba* subsp. *lissophloia* at two ages and to compare these differences to the above ground growth. In addition, the impact of harvesting of the above ground biomass for oil production on the carbon sequestration and growth of the below ground organs was also determined.

E. plenissima and *E. lissophloia* present contrasting stories about the effects harvesting has on biomass sequestration. *E. plenissima* displayed no significant difference between unharvested and harvested trees for lignotuber biomass. Annual re-growth of the above ground biomass for the harvested trees was 4.3 tonnes per hectare per year and unharvested trees recorded only slightly higher average annual growth (5.2 tonnes/km hedge). At age 2.5 years, *E. plenissima* has enough carbon reserves within the lignotuber to fund rapid re-growth after harvesting and establish a leaf area that is large enough to restock the lignotuber and maintain above ground growth..

DECLARATION

I certify that this thesis does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any institution of higher education; and that to the best of my knowledge and belief it does not contain any material previously published by any person except where due reference is made in the text.

Signature.

Date 13/11/1998

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CHAPTER 1

1 INTRODUCTION

1.1 SUSTAINABLE AGRICULTURE

The principle of sustainable agriculture is one that is encompassed by the broader concept of Ecological Sustainable Development. This basic principle states that development should meet the needs of the present without comprising the ability of future generations to meet their own needs (Brundtland, 1988). Sustainable agricultural systems can be summarised as being non-disruptive, self-reliant, appropriate, resilient, productive, profitable, regenerative and stable over time (Roberts, 1995).

Traditional agricultural practices are not sustainable under the parameters of the above concept. Decisions to improve the productivity of agricultural land are made without consideration of the ecological context of the system as a whole (Williams, 1991). This lack of consideration has resulted in land degradation, that is, dry-land salinity, water and wind erosion, soil acidification, soil structure decline and soil nutrient degradation, which are now among Australia's major environmental problems (Bird *et al.*, 1992).

Clearing of deep-rooted perennial plants is seen as the major cause of most land degradation problems. This is particularly well documented for the increase in dry-land salinity and waterlogging (Schofield *et al.,* 1988). In Western Australia, it is estimated that 1.5 million hectares of cleared agricultural land is affected by secondary salinity, this represents approximately 10 % of the entire wheatbelt area and it is estimated that up to 30% could be affected within 30 to 50 years (Agriculture WA *et al.*, 1996). Alternative land use practices that replace annual, shallow rooted crops with deep rooted perennial plants are seen as solutions to secondary salinity, and most other land degradation problems (Bartle *et al.*, 1996). Agroforestry is an alternative that meets these criteria and has the potential to, or currently provides an economic return.

1.1.1 Agroforestry

In Western Australia there are three major agroforestry programs. These programs utilise bluegum, *Eucalyptus globulus* (Bluegums are planted in areas with > 600mm annual rainfall) maritime pine, *Pinus pinaster* (maritime pine is planted in area with 400-600mm annual rainfall) and mallee eucalypts (mallee eucalypts are generically termed "oil mallees" and are planted in areas with 250-400mm annual rainfall) respectively. Bluegums are planted to produce wood chips for the pulp/paper industry. A harvesting cycle consists of two 8-10 year rotations. After the second harvest below ground biomass is removed and the site planted with a new tree. Bluegums can continue to re-coppice after harvest but because of commercial economics it is more profitable to replant after the second rotation and there are plans to replant the entire tree after one harvest (Tym Duncanson personal communication, 1998).

Maritime pine is harvested every 30 years with three thinning harvests in that time. The timber is used in products such as medium density fibreboard (MDF). After 30 years the above and below-ground biomass is removed and the site planted with a new tree (Shea *et al.*, 1998).

1.1.2 "Oil Mallees"

The major difference between the three agroforestry species is that "oil mallees" can be continually harvested because of their ability to rapidly regenerate from epicormic buds on the lignotuber (Noble, 1989). Potentially the above ground biomass can be harvested every two years and the below ground organs will continue to grow. In Victoria, areas of blue mallee (*E. polybractea)* have been harvested for a hundred years from the same below ground root system (Noble, 1989). Mallee eucalypts have adopted this reproductive strategy because of the semi-arid environment they are found in and exposure to the periodic disturbance of fires (James, 1984).

"Oil mallees" are harvested for the eucalyptus oil contained within their leaves. Traditionally eucalyptus oil has been used for medicinal and perfumery applications, with the world supply currently around 3000 tonnes, of which only 3% is supplied by Australia (Franke, 1997). Recent research has identified the potential for cineole (a major constituent of *Eucalyptus* oil) to be used as industrial solvent, replacing ozone damaging and greenhouse gas chemicals such as tri-chloroethane (Barton and Knight, 1997;Wildy, 1996).

1.1.3 Importance of carbon in an agricultural system.

One of the major biological principles of sustainable agriculture is the retention of living organic matter within the farming system (Roberts, 1995). Current, high-input farming practices result in a net export of soil, nutrients, organic matter (carbon) from farming systems (Roberts, 1995). Organic matter retention is important for a variety of reasons but two of the most important within an agricultural framework are firstly, water retention and utilisation. Living carbon within the system intercepts and evapotranspires water which is important in maintaining a balanced hydrological cycle (Bartle *et al.*, 1996). Secondly, nutrient recycling and retention. Living carbon utilises nutrients and decaying carbon binds nutrients allowing greater plant nutrient utilisation and recycling (Roberts, 1995).

The utilisation of tree species such as "oil mallees", that retain below- ground biomass after harvesting and rapidly coppice, could have significant effects on balancing the export of carbon out of a farm system. This permanent store of below-ground carbon also has the potential to offset greenhouse gas emissions.

1.2 CARBON CREDITS

The debate over the effect of global warming has been controversial for the past two decades (AACM International Pty. Ltd., 1997). It has been generally excepted that global warming is caused by the release of carbon based gases into the atmosphere. The primary sources of these emissions are from industrial processes that burn fossil fuels and the destruction of forests for land conversion to agriculture (Shea *et al.*, 1998).

At the 1997 Kyoto Protocol of the 1992 Framework Convention on Climate Change Australia negotiated a greenhouse emissions target of 108% of 1990 levels, to be achieved by the year 2010. This target is seen as difficult to meet because of Australia's dependence on fossil fuel as an energy source (Shea *et al.*, 1998). Due to this difficulty Australia (and other developed nations) argued that activities that remove greenhouse gases from the atmosphere could be used to meet target requirements. For example, reforestation on a large scale has the potential to offset greenhouse emissions by converting CO_2 into carbon sinks within woody plant tissue.

These sinks are generically referred to as "carbon credits". The protocol outlined that these credits could be traded and at current market prices this would be approximately $AUS16 per tonne of carbon.

The fine details of the protocol are yet to be finalised and Australia is yet to ratify the agreement, but it is likely that the below-ground carbon biomass of 'oil mallees' will have the potential for a 100% carbon credit. This is because the below ground organs remain alive and continue to grow after harvesting. This provides a long-term carbon sink (Shea *et al.,* 1998).

1.3 RATIONALE AND OBJECTIVES

"Oil mallees" have a number of implications in terms of environmental management within Western Australia. Firstly, the incorporation of perennial trees on a large scale into the agricultural landscape can assist in balancing the hydrological cycle and other land degradation problems (Bird *et al.,* 1992; Western Australian Salinity Action Plan, 1996). Secondly, harvesting the above-ground biomass can produce an economic return because of the oil contained within the leaves. This oil also has the potential to replace ozone damaging solvents (Barton and Knight, 1997;Wildy, 1996). Finally, "oil mallees" have the potential to offset greenhouse gas emissions, because mallee eucalypts have a sizeable carbon sink, in the form of a root system that continues to grow after harvesting the above-ground growth (James, 1984). These sinks can potentially be traded, providing the landowner with another income source. For "oil mallees" to realise the potential outlined above, there is a need to obtain information on their growth characteristics, particularly that of the below-ground structures. At present little information is available on "oil mallee" eucalypts.

The amount of above-ground biomass production and associated oil yields of three year old "oil mallees" has been studied by Wildy (1996). The proportion of total biomass that this represents has not been established. A study of the below ground biomass will enable the relationship between above and below-ground growth to be established. This will also provide biomass data that can used to determine the carbon benefit of below-ground biomass retention.

The aims of this research are determine the biomass and amount of carbon being sequested by the below ground organs of *E. kochii* subsp. *plenissima* at four different ages and *E. loxophleba* subsp. *lissophloia* at two ages and compare that to the above ground growth. In addition the impact of harvesting of the above ground biomass for oil production on the carbon sequestration and growth of the below ground organs, will also determined.

Specific aims are to:

Aim 1.

Determine the total biomass contained within below ground organs of *E. loxophleba* subsp. *lissophloia* at two age classes and *E. kochii* subsp. *plenissima* at four different ages.

Specifically establish if there is time frame at which the biomass sequestration of the lignotuber slows down.

Aim 2.

Establish the relationship between below ground and above ground growth at 4 different ages of *E. kochii* subsp. *plenissima* and 2 ages of *E. loxophleba* subsp. *lissophloia*.

Aim 3.

Determine the effect of harvesting the above-ground biomass on the biomass sequestration of the above and below-ground organs.

1.4 LITERATURE REVIEW: FUNCTION AND FORMATION OF THE LIGNOTUBER.

The purpose of this literature review is to provide an overview of the knowledge of lignotuber function and formation. This will provide information that will help the reader understand the below-ground biomass sequestration of "oil mallee" eucalypts.

In a Mediterranean climate which characterises the south-west of Western Australia one of the most significant modes of plant reproduction is the re-sprouting strategy (James, 1984; Pate *et al.*, 1989; Noble, 1989). This strategy involves the rapid re-coppice of stem material from a bank of adventitious buds stored below-ground within a swollen root crown area known as the lignotuber (Carr *et al.*, 1982). This re-growth is initiated by the partial or complete removal of the above-ground material and within Australia this is predominately caused by fire (Noble, 1989). Over 95% of Eucalyptus species form a lignotuber and are most pronounced on species that are occur in a mallee form (Webb, 1972). The ability of an individual tree to survive periodic fire is related to root depth, adventitious bud formation and amount of stored carbohydrates (Keeley & Zedler, 1978). It is generally accepted that the 2 primary functions of the lignotuber are as a store of carbohydrates and adventitious buds (James, 1984) though there has been some disagreement within the literature as to the first point.

Carrodus and Blake (1970) concluded that the lignotuber is primarily developed as a source of protected buds. They based this on the premise that the percentage of starch found within the stem and lignotuber of *E. obliqua* seedlings was not significantly different. This conclusion however does not take into account the relative size of the stem and lignotuber. Although concentrations may be equal the absolute amounts of starch will be greater because of the greater volume of the lignotuber. Mullette & Bamber (1978) highlighted this point when looking at mature forms of the mallee, *Eucalyptus gummifera*. Bamber and Humphreys (1965) found that starch levels were very important for tree survival. Then found that starch levels decline during periods of intense foliage growth and a tree that continually has leaves removed will exhaust starch reserves and die.

Pate *et al.* (1990) found when comparing sprouting and seedling strategies that re-sprouters are well adapted to survive fire through their advanced below-ground biomass development, particularly that of the lignotuber. It was also noted that re-sprouters emphasis storage of accessible energy sources over minerals because of the advantage of being able to rapidly re-foliate and send out new roots after fire to exploit water and nutrients at much greater initial rate than seeders. This advantage may not be available within an agroforestry stand of mallee eucalypts because the removal of above-ground biomass is uniform and the root zone will be occupied by other mallees with the same strategy. It does however highlight the basis from which re-sprouters have adapted this reproductive strategy.

1.5 THESIS OVERVIEW

The following chapter describes the study area and site descriptions. Chapter four examines the below-ground biomass sequestration, and chapter five looks at this in context of the above-ground biomass. Chapter six explores the effects of harvesting on below and above-ground biomass sequestration. Chapter seven synthesises the major findings of this study explores the study's findings in terms of carbon sequestration and examines the implications this has on potential carbon credits and the management of "oil mallees" agroforestry systems.

CHAPTER 2

2 STUDY SITE SELECTION.

2.1 BACKGROUND

In 1993 the Department of Conservation and Land Management (CALM) in partnership with the Western Australian Oil Mallee Association established 15 oil mallee trial sites with 9 species per site. These were located on private land that was previously used for agricultural production and on soil types that were typical to the area (Wildy, 1996). These trial sites are located throughout the wheatbelt area of south-west Western Australia, and included Canna, Kalannie, Narrogin-Wickepin, Narambeen, Woodanilling and Esperance (Arborescence Consultancy, 1996). These areas now incorporate the major oil mallee growing regions (Figure 2.1).

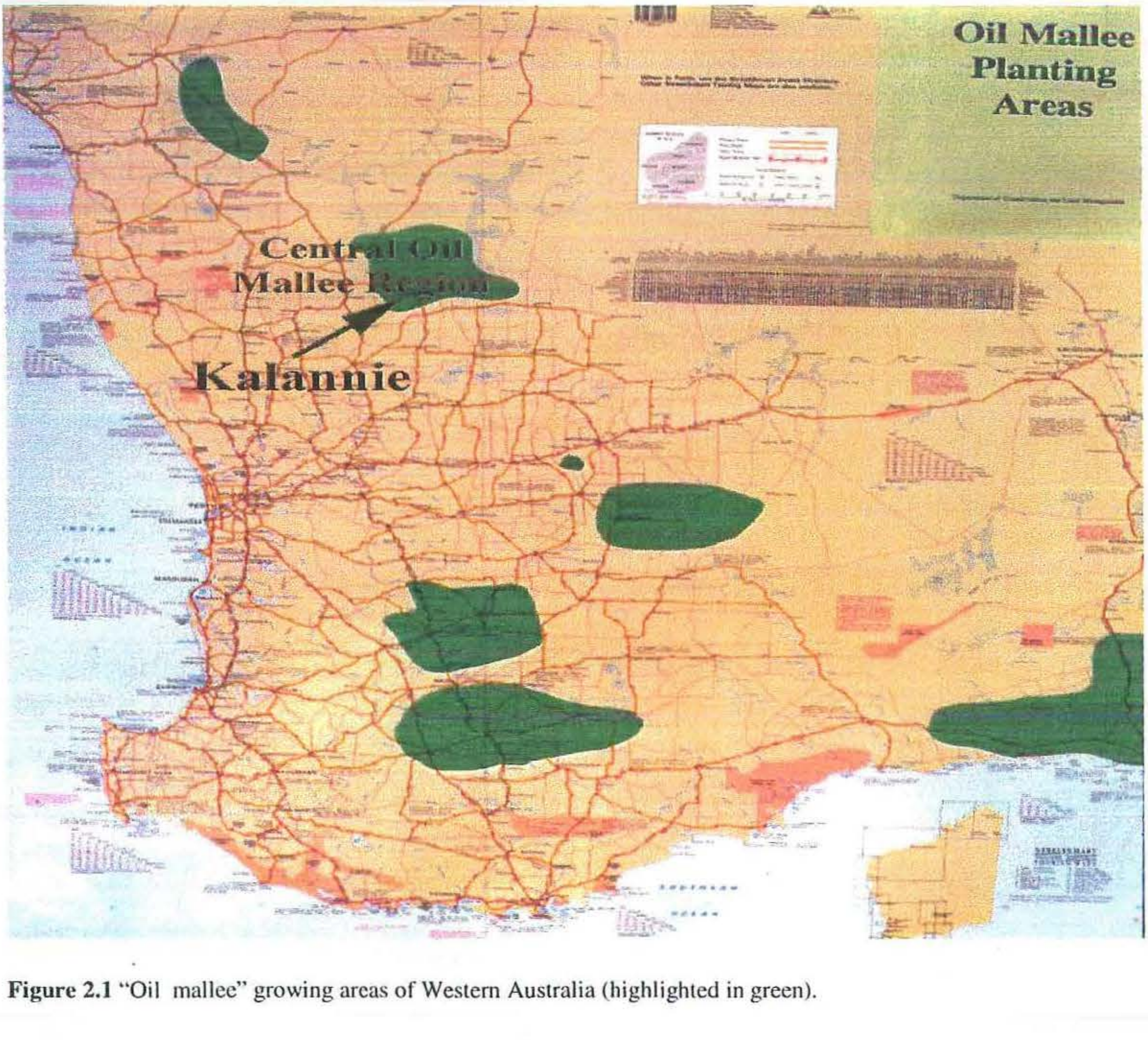


Figure 2.1 "Oil mallee" growing areas of Western Australia (highlighted in green).

2.2 STUDY AREA SELECTION

There were a number of selection criteria that were used to evaluate the potential of study areas. These were, firstly that the area needed to be within the low rainfall zone (250mm–400mm annual rainfall) of the wheatbelt. The low rainfall zone is the area that "oil mallees" have the greatest planting potential. This is because current commercial species are not endemic to that area and can't survive in a low rainfall climate. Secondly, existing plantations of "oil mallees" were essential. Finally, landowners needed to be willing to allow the destruction of small areas of their plantings.

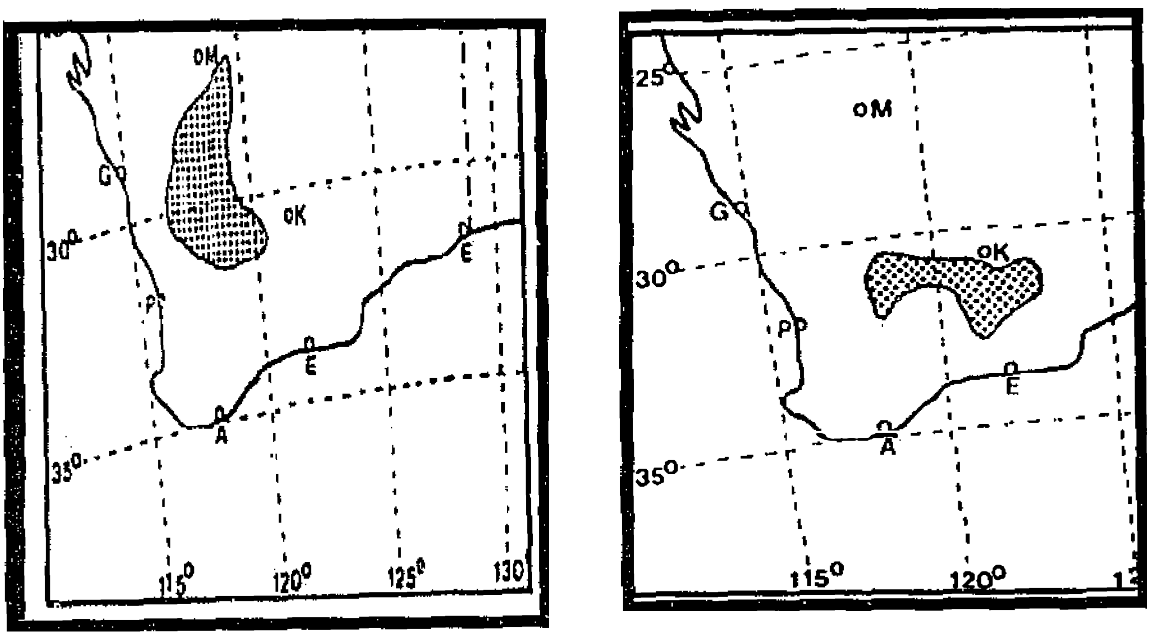
The study area is located within the "Central oil mallee" region (Figure 2.1). The town of Kalannie is the "oil mallee" planting centre of this region and is approximately 350 kilometres north-east of Perth. The average yearly long-term rainfall is 311 millimetres. The two major soil types of the area are deep yellow sands and red brown loams (Clarke, 1997) with most species of mallee planted on both soil types. The region has planted approximately four million oil mallee trees, utilising a variety of species, since 1993.

2.2.1 Species selection

The two species chosen for this study were *E. kochii* Maiden & Blakely subsp. *plenissima* Gardner and *E. loxophleba* subsp. *lissophloia* L. Johnston & K. Hill. They will be referred as *E. plenissima and E. lissophloia* respectively for the remainder of this thesis.

E. plenissima is endemic to Western Australia and is a member of the oil mallee series, Oleosae in the classification of Pryor and Johnson (1971). It is referred to as an Oil Mallee. Its distribution is widespread throughout the northern and eastern wheatbelt and natural stands can be found within the study area (Brooker & Kleinig, 1990). (Figure 2.2a)

In Western Australia *E. lissophloia* was found to have the highest above ground biomass growth to age three, over of a range of site conditions compared to a number of different species (Wildy, 1996). *E. lissophloia* is endemic to Western Australia and is a member of the York gum series, Loxophlebae. Its common name is the smooth barked York gum. Its distribution is sporadic throughout the eastern wheatbelt and goldfields and its natural habitat is on heavier soils throughout the landscape (Brooker & Kleinig, 1990)(Figure 2.2b).



a b

Figure 2.2 Distribution of *E. plenissima* (a) and *E. lissophloia* (b).

Both species were chosen because they are widely used in commercial plantings and their representation of a number of other commercial species. *E. plenissima* is morphologically and ecologically similar to *E. kochii* subsp. *kochii* and *E. horistes*. These species are more distinguished by their distributions than by obvious taxonomic characters (Wildy, 1996; Brooker & Kleinig, 1990). *E. lissophloia is* very similar to

E. gratiae, with similar leaf chemistry and landscape position. This representation may allow conclusions drawn from this study to apply over a wider area.

2.2.2 Study Sites

Four study sites were used within the study area. All are located within a 25 kilometre radius of the Kalannie town centre. The sites represent different ages since planting. These ages are 2 years ("Cail"), 4 years ("I. Stanley"), 5years("D. Stanley") and 6 years ("Rolinson") respectively. These age classes were chosen so as to record the progression of biomass sequestration with time. To date only growth information to age three has been attained for "oil mallees". By looking at older trees it is hoped to determine a longer term growth pattern. This will enable age comparisons to be made between tree characteristics.

Of importance was the uniformity of soil type and characteristics at each site. Soil analysis was performed for each site (refer to methods for techniques) to determine soil characteristics. This was done so that differences in total carbon sequestration can be attributed to the age of the tree rather than site factors. Each site was observed to be deep yellow sand.

The planting configuration at each site was 2 rowed hedges, with alleys of crop between each hedge (Figure 2.3). The exception to this was "Rolinson" which was a block planting with double rowed hedges spaced 5 metres apart. To account for this only the row directly adjacent to the crop was sampled so as to have similar fertiliser application, chemical spraying frequency and competition to the alley of crop as the other sites.

All four sites had *E. plenissima* present but only "I. Stanley" and "D. Stanley" had both *E. plenissima* and *E. lissophloia*. Unfortunately, *E. lissophloia* was not planted on deep yellow sands for the 2 year and 6 year age classes. This limits any longer term conclusions to be drawn for *E. lissophloia* but examining this species at age four and five will provide important information and enable a comparison of the two species at these ages.

Figure 2.3 The most commonly used configuration for "oil mallee" plantings. Each hedge has two rows of trees, 2.5m apart. There are approximately 1200 trees per kilometre of hedge. The distance between hedges may vary depending on the site conditions and the landowners needs.

CHAPTER 3

3 METHODS.

This chapter explains all the methods that were used for this project. It has been incorporated into one chapter rather than explained within individual chapters because the methods were for the most part uniform in meeting all the aims of this project. To avoid confusion, the aim that each method was applied to will be stated and any limitations of that methodology explored.

3.1 SOIL ANALYSIS

All sites were tested for soil characteristics. This involved samples being taken from one excavated pit per age class. Each pit was approximately one metre deep, with the depth of each soil horizon measured and two random soil samples taken from each horizon and classified using Northcote's scheme (1979). The "A" horizon is referred to as "topsoil" and the "B" horizon is referred to as "subsoil".

A simple soil moisture rating for each sample was used, classifying a dry soil as (1) to a wet soil profile (5). Each horizon sample was sent to CSBP and analysed for phosphorous (P), nitrogen (N), potassium (K), iron (Fe), organic carbon (OC), pH and conductivity, following the methods outlined in Rayment and Higginson (1992).

The results of the soil analysis are presented within appendix one.

3.2 EXPERIMENTAL DESIGN

At each of the four sites five *E. plenissima* trees were randomly chosen. At sites "I. Stanley" and "D. Stanley" five *E. lissophloia* trees were randomly chose (Table 3.1).

Table 3.1 Experimental design with no of tree replicates for each age category and species (n/a= site not available).

	Age 2	*Age 4*	*Age 5*	*Age 6*
E. plenissima	5	5	5	5
E. lissophloia	n/a	5	5	n/a
Harvested *E. plenissima*	n/a	n/a	5	n/a
Harvested *E. lissophloia*	n/a	n/a	5	n/a

This design was chosen to determine changes in above and below-ground growth with time. This has important implications for management of "oil mallee" plantings.

For the harvested versus non-harvested treatment, five trees for both species were randomly chosen from the ten individuals that were available. The harvested trees were on the "D. Stanley's" five year old site. These trees were initially harvested in January 1996 at age 2.5 years and this harvest was done July 1996 a further 2.5 years of coppice growth. The harvested treatment was designed to compare one population of trees that had been treated .

All trees were sampled using the same methods, which are outline below.

3.3 BIOMASS SAMPLING TECHNIQUES.

3.3.1 Above ground biomass

The above ground biomass for each tree was separated from the below ground biomass at the soil surface with a chainsaw. The total above ground biomass was weighed immediately and the green weight recorded. To determine the leaf /stem ratio all trees from each age category were processed using methods outlined in Wildy (1996, p18). This required the separation of the thicker wood stems (with leaves removed) from the remaining mass of twigs and leaves. The larger stemmed material was immediately weighed and the weight of the remaining twigs and leaves calculated. A sub-sample of leaves and twigs (approximately 500grams) was separated into these two categories and immediately weighed and bagged. The ratio that this sub-sample represented was used to determine the total weight of the leaf and twig components. Five sub-samples of stem were also immediately weighed and bagged. All sub-samples were oven dried so as to determine wet weight/dry weight conversions.

These methods apply to aims two and three. According to Wildy (1996) this sampling method determines the total weight of the three major tree components with a high degree of accuracy. The division of the tree components enables comparison of the relative growth of these areas of the tree. This is important in the context of the "oil mallee" as the total leaf weight is positively correlated with the amount of oil contained within the tree (Wildy, 1996).

3.3.2 Below ground biomass.

3.3.2.1 Plot Design

Figure 2.4 displays the plot design for the below ground sampling of each tree. The plot is divided up into 3 areas. The size of sampled square around each tree was determined by the distance between the rows (approximately 2.5 metres) and the distance to neighbour trees on either side of the sampled tree (approximately 1.3 metres). The area sampled was equidistant to the above factors and extended 1.0 metre from the centre of the row. This area was therefore 1.3 metres by 2.25 metres.

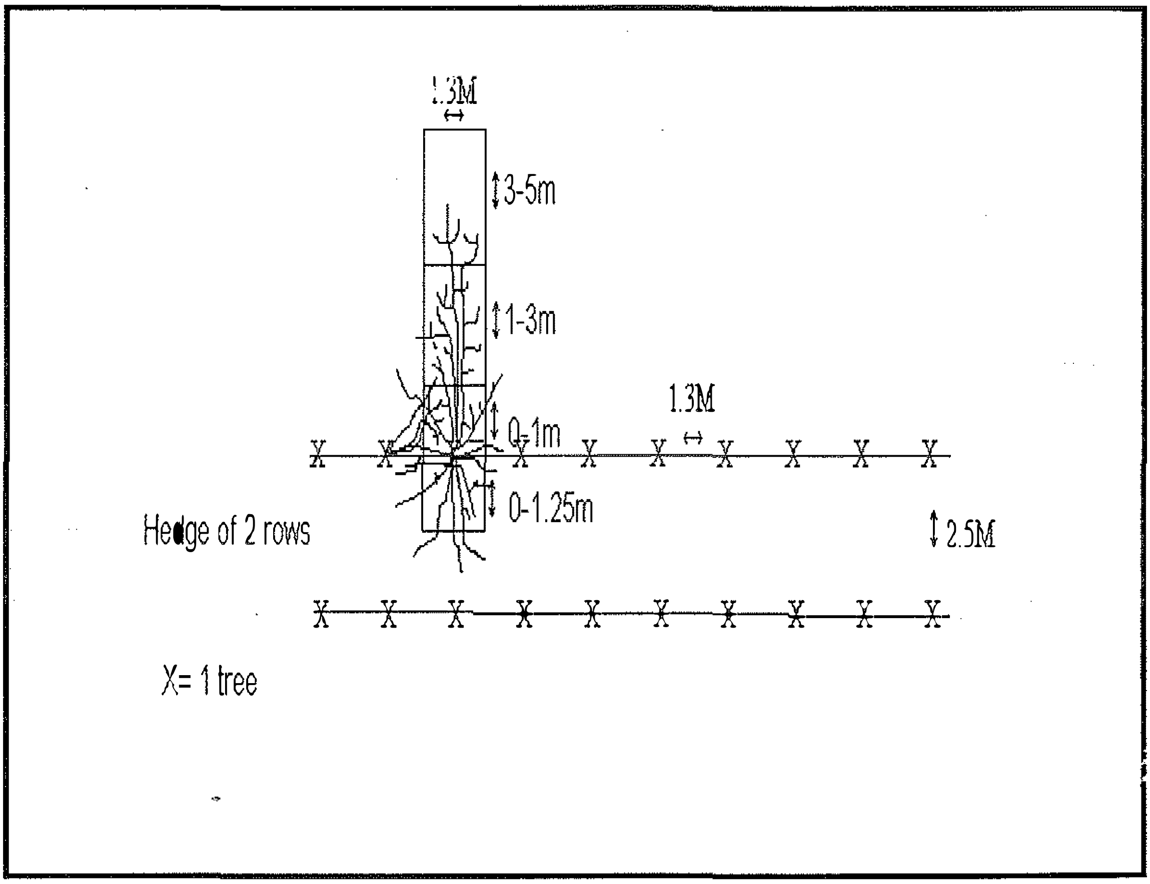


Figure 2.3 Below-ground biomass sampling plot design.

This area was excavated to depth of 1.0 metres. From this point the sampling area extended out at 2 metre intervals to a distance of 5 metres and these zones were sampled to a depth of 0.5 metres. The biomass from each zone was treated separately using the methods described below.

The plot design was applied to determine results for all four aims. It has limitations because the below-ground sampling of trees was logistically very difficult. Over 160 tonnes of soil were sampled. The sampling design used was the best available given time and monetary constraints. This design has assumed that the amount of roots belonging to sample tree that are outside the sample plot would be approximately equal to roots coming into the sample plot from neighbouring trees. This sampling method is most likely an underestimate of the total below-ground biomass. The depth sampled was one metre in the plot around the tree, but it was observed that taproots extended past this point. The backhoe was able to excavate to 2.5 metres, but this extra depth required twice the time to sample as sampling the rest of the soil area.

3.3.3 Root sampling.

All below ground organs were sifted on a metal weld mesh sieving table (Figure 2.4). The table is 2.1 metres by 1.4 metres and the individual squares are 25mm by 25mm. To check the amount of fine root material that was moving through the sieve a random, one kilogram sample of slag soil was sieved using a 2mm diameter soil sieve.

For the first plot the below ground organs were separated into lignotuber and roots. The lignotuber volume was calculated by measuring the length and width at the widest point by the width at 90 degrees to this point. The two remaining plots only have roots within them. All samples were cleaned, weighed and the total green weight for each category recorded. Sub-samples from each root zone were bagged and weighed(approximately 500 grams). These were then oven-dried and re-weighed to obtain mean percentage moisture and mean dry weights. These results were used for conversion to total dry weight of the two components for each tree.

These methods apply to results within all four aims. By using these methods root material were easily sorted and importantly captured most of the fine root material.

Figure 2.4 Sieving table with a sample of soil being place on it by the bobcat.

3.4 Oven drying

All sub-samples were dried at a constant temperature of 70 degrees Celsius in a drying oven until constant weight was achieved. This took approximately 2 weeks for the roots and lignotubers samples.

3.5 TOTAL ORGANIC CARBON

Total organic carbon was determined using the ash-free dry weight method. Five sub-samples from each component of every tree were milled to a 2mm diameter using a grinding mill. The sub-samples were then re-dried for 48 hours to ensure that all water was removed and then weighed. Each sub-sample was placed in a high temperature kiln for 60 minutes at 505 degrees Celsius until only the mineral content remained. A three gram sample of 100% glucose was placed in the oven with every firing to ensure total combustion of all organic carbon (Downing & Anderson, 1985). Total organic carbon was calculated by subtracting the final weight from the initial dry weight.

Total organic carbon was determined to achieve aim 4. Total organic carbon represents the total carbon contained within a sample. This was done so as to determine differences between the total organic carbon content of tree components between ages and species.

3.6 ANALYSIS OF VARIANCE.

For each age classes and component category means were calculated. Within age variation was determined by calculating standard error.

To test for significant differences between age classes and species ANOVA tests were performed. Significant differences cited in the text imply a 95% or greater level of confidence.

CHAPTER 4

4 Below Ground Biomass Sequestration

4.1 Introduction

Most studies of tree morphology, ecology and physiology concentrate on the study of above-ground components of the plant and neglect to gain an understanding of the root system (Dickmann & Pregitzer, 1997). Below-ground organs are part of an integrated system. Water, minerals, amino acids, carbohydrates, growth regulators and other organic substance are exchanged freely between the above and below-ground plant components (Dickmann & Pregitzer, 1997).

Despite its importance, little information is available on the root systems of most agroforestry species.. The roots of mallee eucalypts are particularly important as the root systems is the basis of their reproductive strategy of "re-sprouting" (James, 1984). This strategy relies on the protection of a store of epicormic buds below the soil surface within the lignotuber and thus protected from fire. After a disturbance event the epicormic meristems use the centrally stored carbon (starch) within the lignotuber to quickly grow. This rapid growth enables an individual to utilise the post-fire nutrients thus out-compete neighbouring trees for site dominance. Without this capacity a tree is in trouble in terms of long-term survival and growth and thus it is vital to attain a large store of carbon as quickly as possible (Mullette and Bamber, 1978). Fast carbon sequestration at an early age within the lignotuber is comparable to fast shoot growth utilised by other reproductive strategies, such as seeders (Pate *et al.*, 1990).

Given the importance of below-ground biomass accumulation, it is hypothesised that the preferential apportioning of productivity towards the growth of the lignotuber will continue until a critical point of storage that can sustain future re-growth is reached. Growth will not stop after this point but slow down and be re-directed towards coppice growth and root expansion.

For a manager of an "oil mallee" plantation this information is vital so as to time the first harvest with the point in time where the below-ground carbon stores are large enough to drive vigorous re-coppice without diverting productivity to the recovery of the lignotuber. This will maximise future above-ground growth and therefore leaf biomass which inturn maximises the economic return from harvesting.

Another important aspect of the below-ground components is the spatial distribution of the root system of "oil mallee" plantings. This will give an indication as to the degree of competition between trees and crops. The root zone is vital for nutrient and water uptake and thus oil mallee roots may out-compete traditional crops because of the large root systems that are permanently within the soil zone.

There were a number of difficulties in obtaining this information. This primarily due to below-ground sampling of trees being logistically very difficult. Over 160 tonnes of soil were sampled. The sampling design assumed that the amount of roots belonging to sample tree that are outside the sample plot would be approximately equal to roots coming into the sample plot from neighbouring trees. This sampling method is most likely an underestimate of the total below-ground biomass. The depth sampled was one metre in the plot around the tree, but it was observed that tap roots extended past this point. The backhoe was able to excavate to 2.5 metres but this extra depth required twice the time to sample as sampling the rest of the soil area. With those limitations considered the aim of this chapter is,

Determine the total biomass contained within below ground organs of *E. loxophleba* subsp. *lissophloia* at two age classes and *E. kochii* subsp. *plenissima* at four different ages.

Specifically establish if there is a point in time at which the biomass sequestration of the lignotuber slows down.

4.2 RESULTS

4.2.1 E. plenissima

The growth of the lignotuber biomass recorded for accelerated sequestration to age five then a slowing of the mean annual increment between age five and six (Figure 4.1). Age six recorded the highest mean lignotuber with 2.99 tonnes per kilometre of hedge but the difference between age five and six was not significant (P=0.139). There was significant differences between ages two, four and five respectively (P<0.05). This indicates that growth is slowing down after age five.

The total above-ground growth displayed a similar growth pattern to the lignotuber (Figure 4.2). Between ages two and four the average annual increase in total biomass was 2.14 tonnes per kilometre of hedge which is a significant difference (P<0.05). Biomass at age five was recorded as 7.41 tonnes per kilometre of hedge, an average annual increase of 2.96 tonnes per kilometre of hedge (significant difference P<0.05). Growth between ages five and six slowed by more than a half the previous increase (1.16 tonnes per kilometre of hedge). There is no significant difference between ages five and six (P= 0.423) with the below-ground biomass recorded at 8.57 tonnes per kilometre of hedge.

The relationship between lignotuber biomass and total below-ground biomass is strongly correlated (r^2=0.8955)(Figure 4.3). *E. plenissima* below ground biomass increase by around 1.3 kilograms per tree with every 0.5 kilogram of increased lignotuber biomass.

Over 75 percent of the total roots were found within the zone around tree (x-1m) for all ages. The biomass ranged from 0.09 tonnes per kilometre of hedge at age two to 4.86 tonnes per kilometre of hedge for age six. Ages two, four and five were all significantly different (P<0.05) but the mean biomass was not significantly different between age five and six (P=0.410). The amount of root biomass that was within the cropping zone (1-5 metres) was on average 22.5%, 12.5% and 12.7% of total root biomass for ages four, five and six respectively. Within the 1-3 metre sampling zone there was not significant difference between age classes (P>0.05), with the average over the ages being 0.57 tonnes per kilometre of hedge. The 3-5m root zone recorded substantially less root biomass with the average across the ages being 0.14 tonnes per kilometre. There was not a significant difference for root biomass between age classes (P>0.05). The relatively small amounts of root biomass increase within the cropping zone (1-5 metres) compared to the annual increases in total below-ground biomass sequestration indicate that most growth is occurring with the zone directly around the trees.

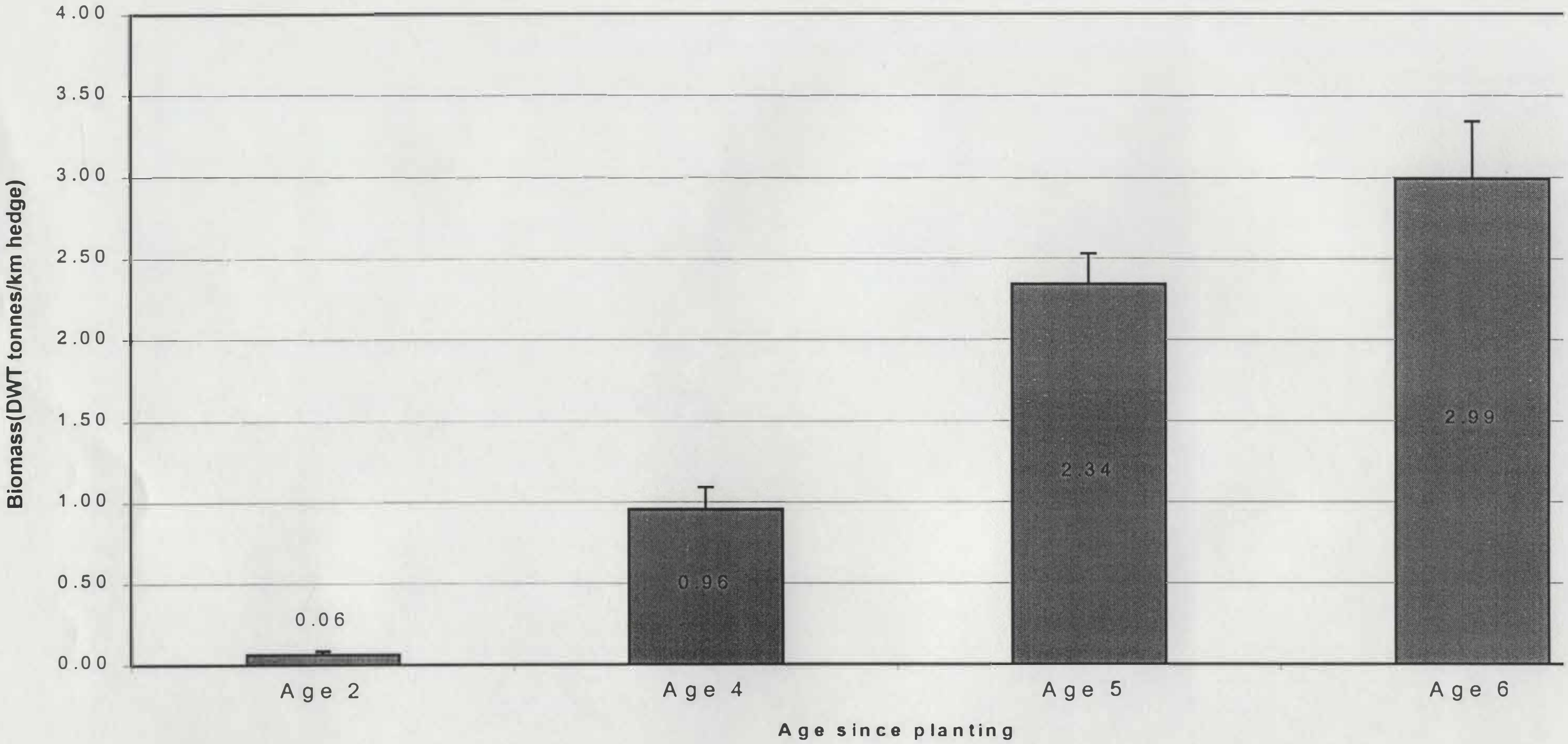


Figure 4.1 Mean lignotuber biomass for *E. plenissima* at various ages with standard error.

Figure 4.2 Mean total below-ground biomass for *E. plenissima* at various ages with standard error.

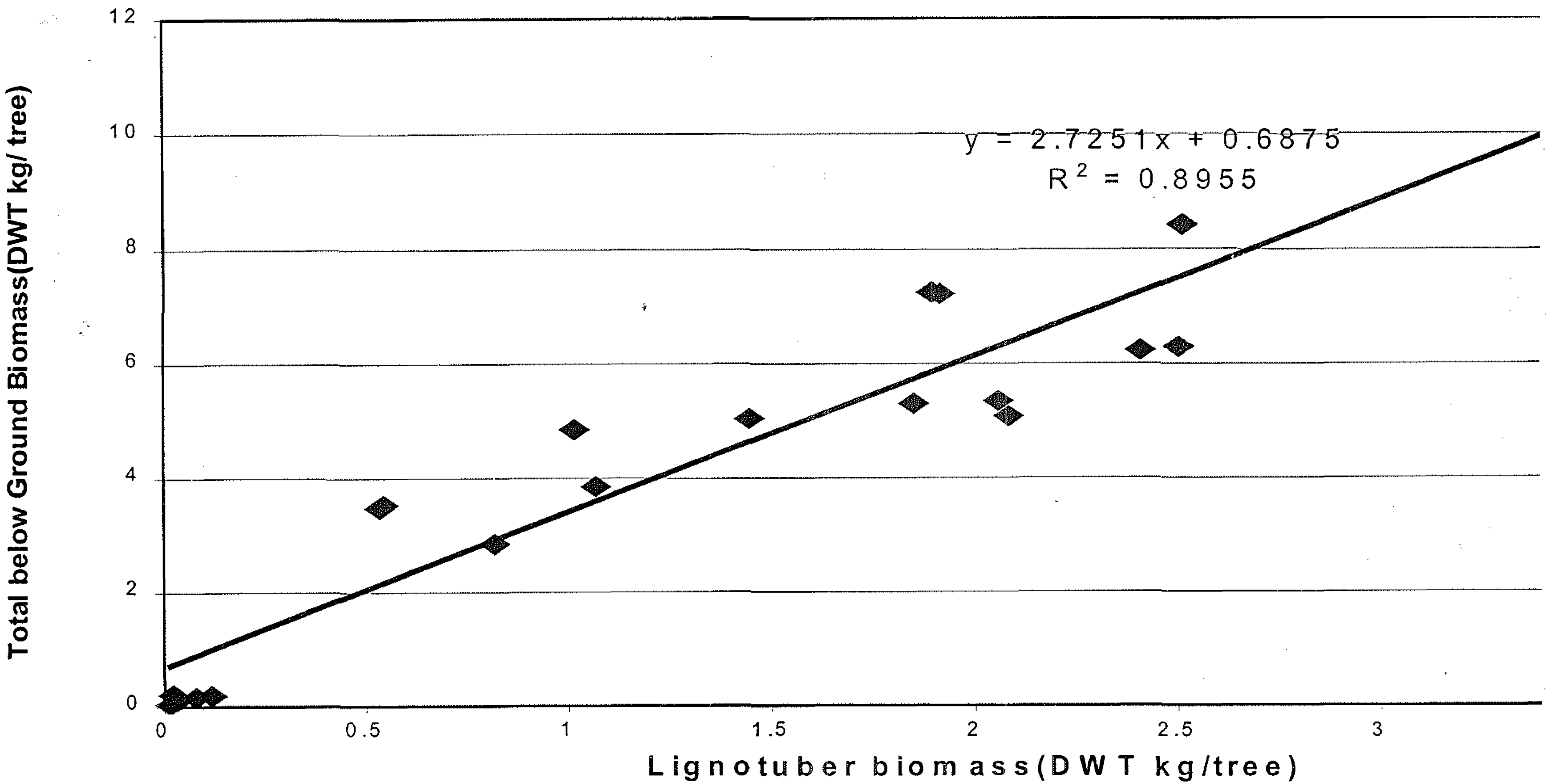


Figure 4.3 Regression analysis between lignotuber biomass and total roots per tree over all ages of *E. plenissima.*

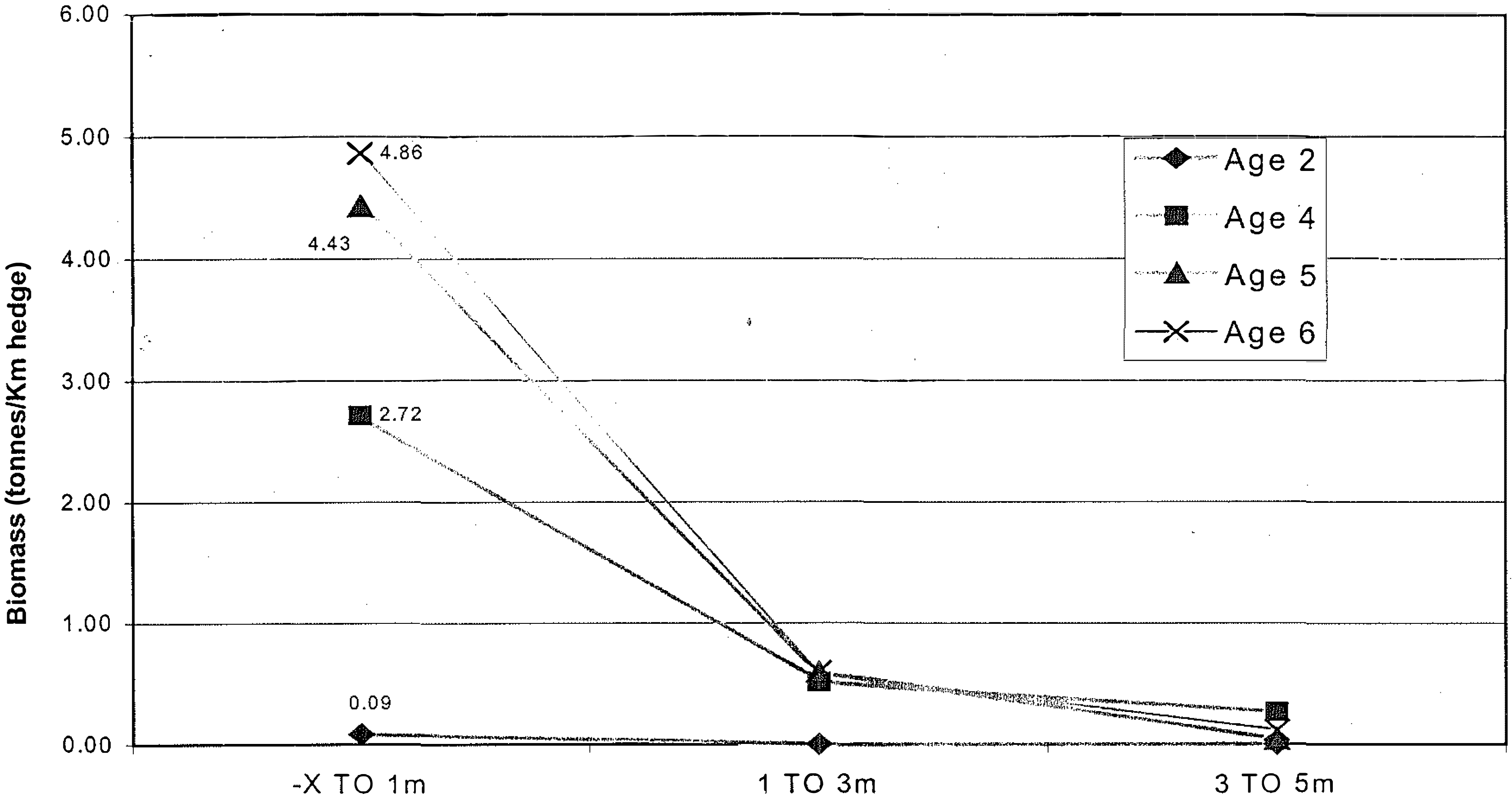


Figure 4.4 Mean total roots within each sampling zone for *E. plenissima* at various ages.

4.2.2 *E. lissophloia*

The total below-ground biomass of *E. lissophloia at* age five (Table 4.1) was greater than at age four by almost 4.9 tonnes per kilometre of hedge but this difference was not significant (P=0.10). The lignotuber biomass recorded at age five was significantly higher than at age four (P=0.05) with an average lignotuber biomass recorded at age five of 4.88 tonnes per kilometre of hedge. The relationship between total root biomass and lignotuber biomass recorded a change between ages, with 7.6 % more lignotuber biomass found within the roots system at age five than age four.

Table 4.1 Mean biomass and percentage of the total below-ground biomass (tonnes per kilometers of hedge) of *E.lissophloia.* that the lignotuber and total roots represent for trees age four and five respectively.

	4 years		5 years		P values
	mean	%	mean	%	
Total roots	4.554	63.8	6.259	56.2	0.10
Lignotuber	2.609	36.2	4.882	43.8	0.05*
Total B/G biomass	7.154	100%	11.141	100%	0.063

* denotes significant difference.

Although the change in total below-ground biomass between ages was not significant (P=0.063) there was still a substantial increase in total biomass. This indicates that the growth of *E. lissophloia* has yet to plateau and accelerated growth will continue.

The relationship between the size of the lignotuber and total below-ground biomass (Figure 4.5) is strongly positively correlated (r^2=0.9743). A one kilogram increase in the size of the lignotuber is accompanied by a 1.2 kilogram increase in size of the rest of the root system. This indicates that the larger the size of the lignotuber the greater the size that the root biomass around that lignotuber will be.

The spatial distribution of root biomass is displayed within Figure 4.6. At age five *E. lissophloia* recorded 5.24 tonnes per kilometre of hedge of root biomass within the sampling zone around the tree (X-1m). A further 18.4 % of total root biomass was found within the cropping zone (1-5m). The root biomass within trees aged four (3.50 tonnes/km hedge) was less than age 5 trees but this difference was not significant (P=0.082). There was a further 0.9 tonnes per kilometre of hedge within the root zone (1-5metres) which is 20.2 % of the total root biomass at age four.

4.2.3 E. plenissima & E. lissophloia

E. lissophloia recorded significantly more lignotuber biomass than *E. plenissima* at ages four and five ($P<0.05$). On average the lignotuber biomass recorded was three times more for *E. lissophloia* at age four than *E. plenissima* (Figure 4.7). The size of the lignotuber at age 5 for *E. lissophloia* was greater than that recorded at age six for *E. plenissima*

The total below-ground biomass recorded was larger in *E. lissophloia* than *E. plenissima* at both ages (Figure 4.8), but the difference is not significant (P=0.105 & 0.145 respectively).

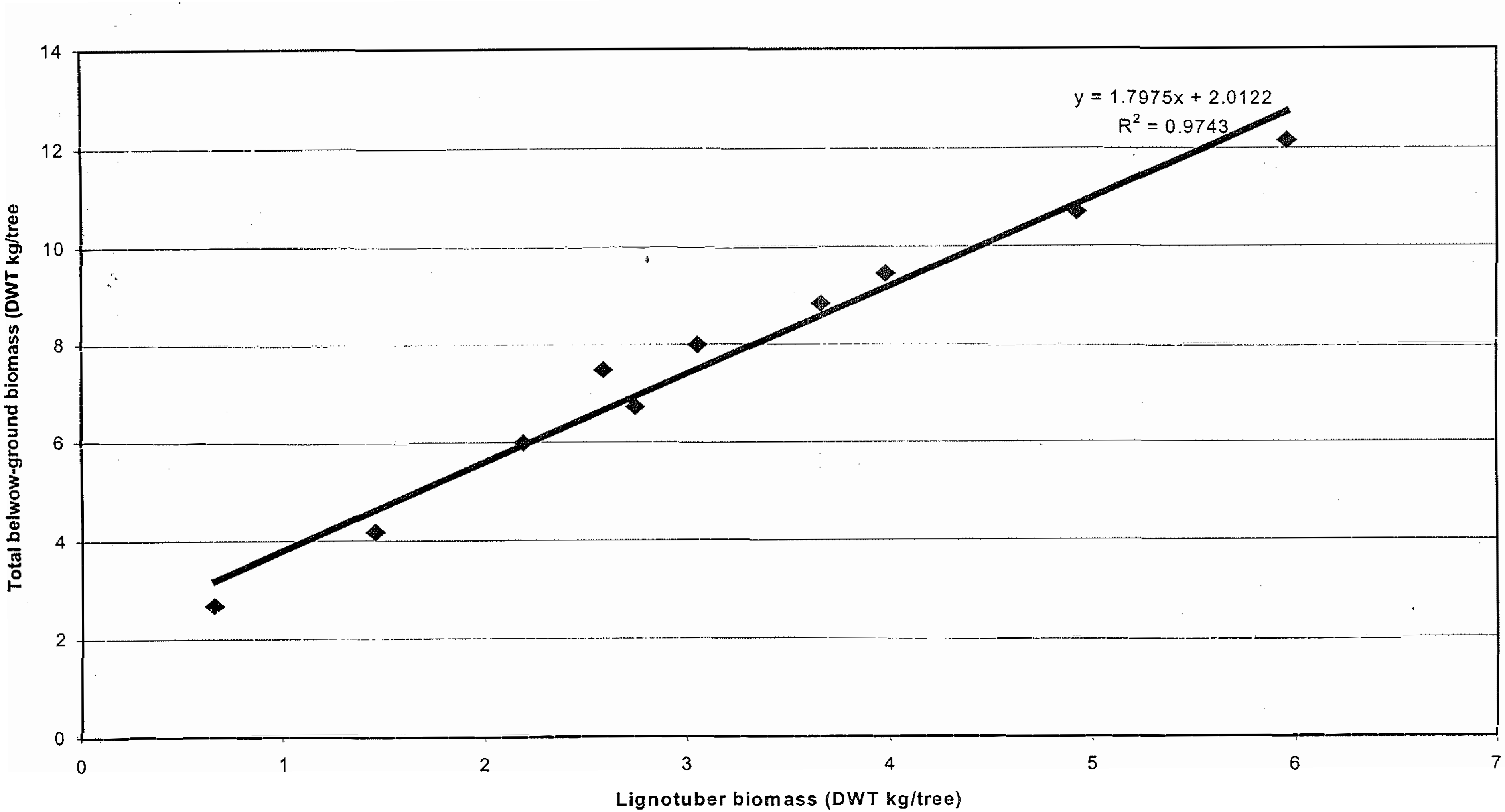


Figure 4.5 Regression analysis between lignotuber biomass and total roots per tree over all ages of *E. lissophloia.*

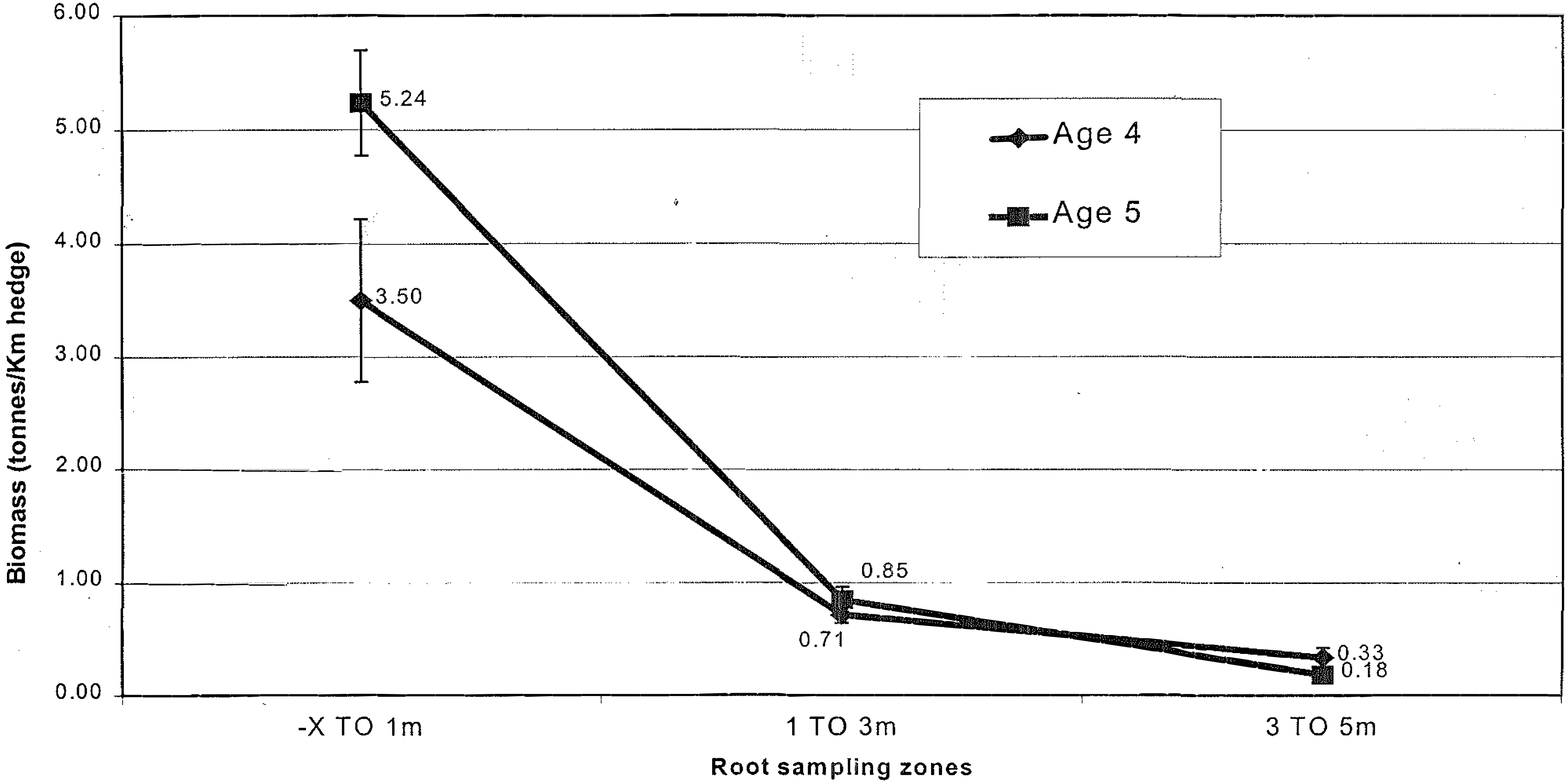


Figure 4.6 Mean total roots within each sampling zone for *E. plenissima* at various ages.

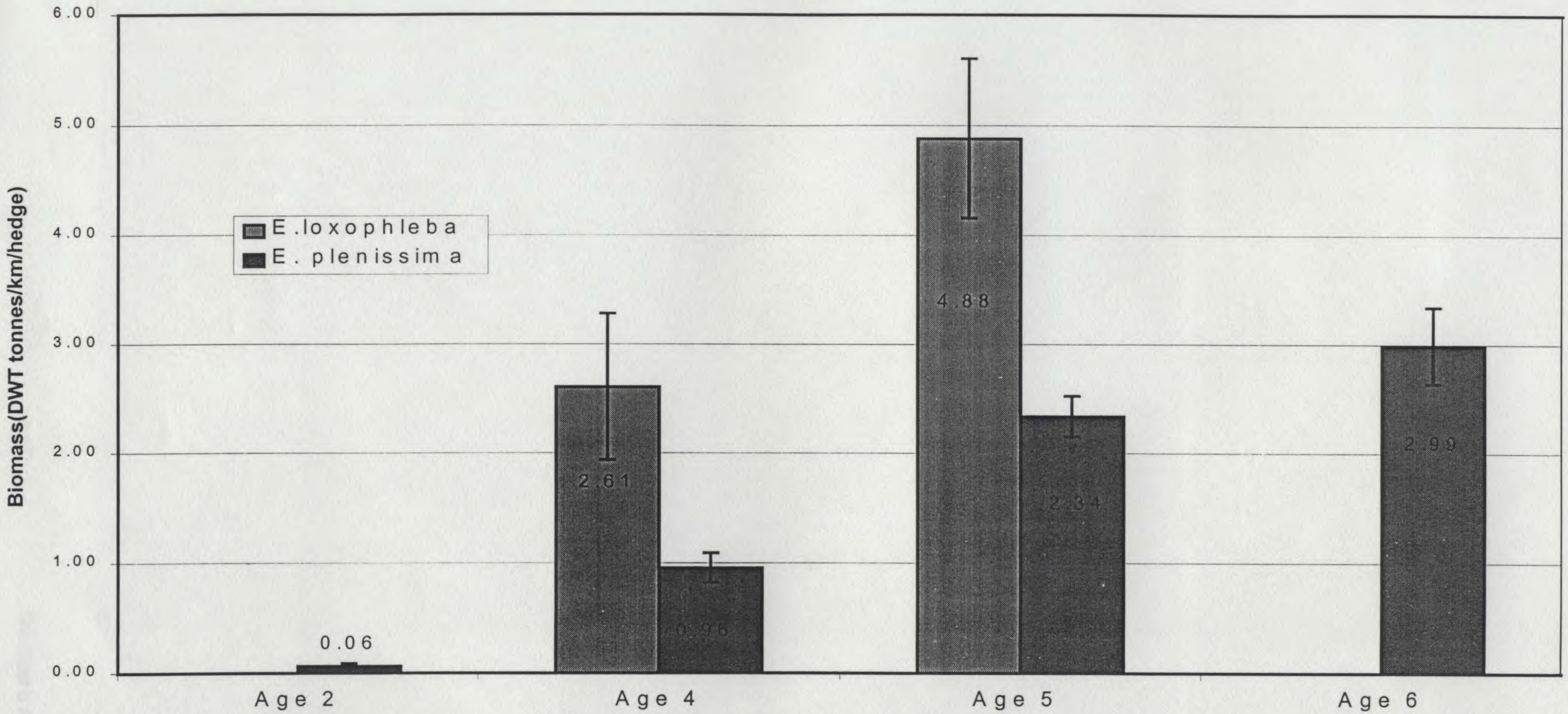


Figure 4.7 Mean lignotuber biomass for *E. plenissima* and *E. loxophleba* at various ages.

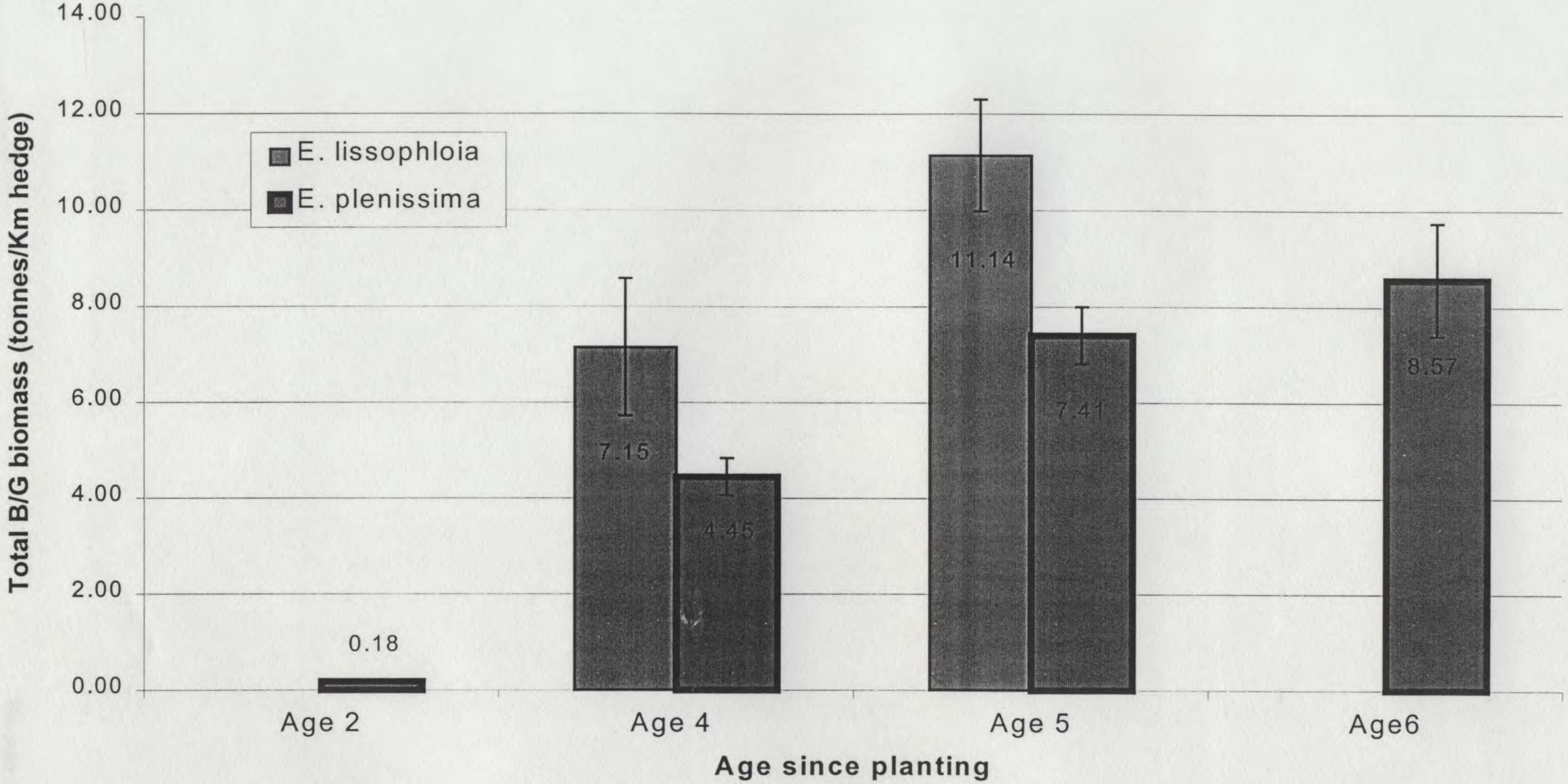


Figure 4.8 Mean below-ground biomass for *E. plenissima* and *E. loxophleba* at various ages

4.3 Discussion

The annual rate of growth recorded for below-ground biomass and lignotuber biomass of *E. plenissima* was maximised at age five. On average 7.41 tonnes per kilometre of hedge was within the below-ground structures and the lignotuber was 2.34 tonnes per kilometre of hedge. Growth between ages five and six halved when compared to age four to five. These results indicate that age five is the critical point of biomass sequestration. Growth of below-ground structures will continue once critical point of storage is reached. By modeling the annual increase recorded for lignotuber biomass between age five and six over 100 years, assuming that this is constant over that time a hedge planted with *E. plenissima* will contain 68 tonnes of lignotuber biomass per kilometre. This is equivalent of 56.0 kilograms per tree. Three remnant *E. plenissima* were sampled to assess the long-term direction of growth. The age was not possible to determine and only the lignotuber biomass and total above-ground growth was recorded. The average lignotuber size was 166.0 kg per tree. This indicates that there will be large stores of permanent carbon within an "oil mallee" system.

The root biomass within the cropping zone (1-5m) was very small compared to the main area around the tree for both *E. plenissima* and *E. lissophloia*. *Based* on this the competition between tree roots and crop roots is most probably not significant enough to cause a reduction in crop yields. Bird *et al.*, (1992) found that alleys of trees within agricultural land actually increased production by reducing wind speed and thus preventing wind erosion. Any root competition effects will be compensated for by increases in production associated with gains in the retention of organic matter within the soil. Organic matter retention stabilises soils and prevents wind and water erosion which are major land degradation problems throughout Australia (Roberts, 1995).

The point of critical growth could not be determined *E. lissophloia* for because only two age classes were sampled. From the data it appears that *E. lissophloia* has accelerated growth within the lignotuber, but the root biomass growth has not increased significantly between age four and five. If the critical growth has not been reached then *E. lissophloia* has great potential to expand below-ground growth in the future. The lignotuber at age 5 was double that of *E. plenissima* at age five and 1.5 times the size at age six.

The static nature of sampling technique prevents definite conclusions from being drawn for the data. Growth is continuous within plants and examining biomass with one off harvesting events of different age trees will not give an accurate account of biomass sequestration. However given these limitations it is still a reasonable conclusion that at age five *E. plenissima* has reached a critical level in the size of the lignotuber and any harvest event after this time will not affect the ability of *E. plenissima* to re-coppice and maintain and increase the size of the below ground lignotuber.

CHAPTER 5

5 ABOVE GROUND AND BELOW GROUND COMPARISONS

5.1 INTRODUCTION

Above-ground growth within an 'oil mallee' system is important for a number of reasons. Firstly it is an indication of the photosynthetic capability of a tree in terms of the total leaf area. This can give an indication of the water use of a plant (Pettit & Ritson, 1992). The total leaf biomass is also positively correlated with the oil content within a tree (Wildy, 1996).

Secondly, the above ground growth will experience a slowing down of total biomass sequestration that is related to the below-ground growth. Within chapter three the amount below-ground biomass was established for both study species. The proportion of total biomass that this represents is not known. Therefore the aim of this chapter is to

Establish the relationship between below ground and above ground growth at 4 different ages of *E. kochii* subsp. *plenissima* and 2 ages of *E. loxophleba* subsp. *lissophloia*.

Specific aims are to determine if there are any changes in the distribution of productivity in terms of changes in the percentage composition that various components represent.

5.2 RESULTS

5.2.1 E. Plenissima.

The progression of biomass sequestration of *E. plenissima* displayed a similar pattern for all tree components (Figure 5.1). This growth pattern was accelerated growth to age four then decreased in annual growth (4.7 tonnes/km hedge) between age four and five. The total tree biomass recorded for each age was 0.98, 18.03, 33.16 and 37.86 tonnes per kilometre of hedge for ages two, four, five and six respectively. There was not a significant difference between age four and five (P=0.442) and all other ages displayed significant differences (P<0.05).

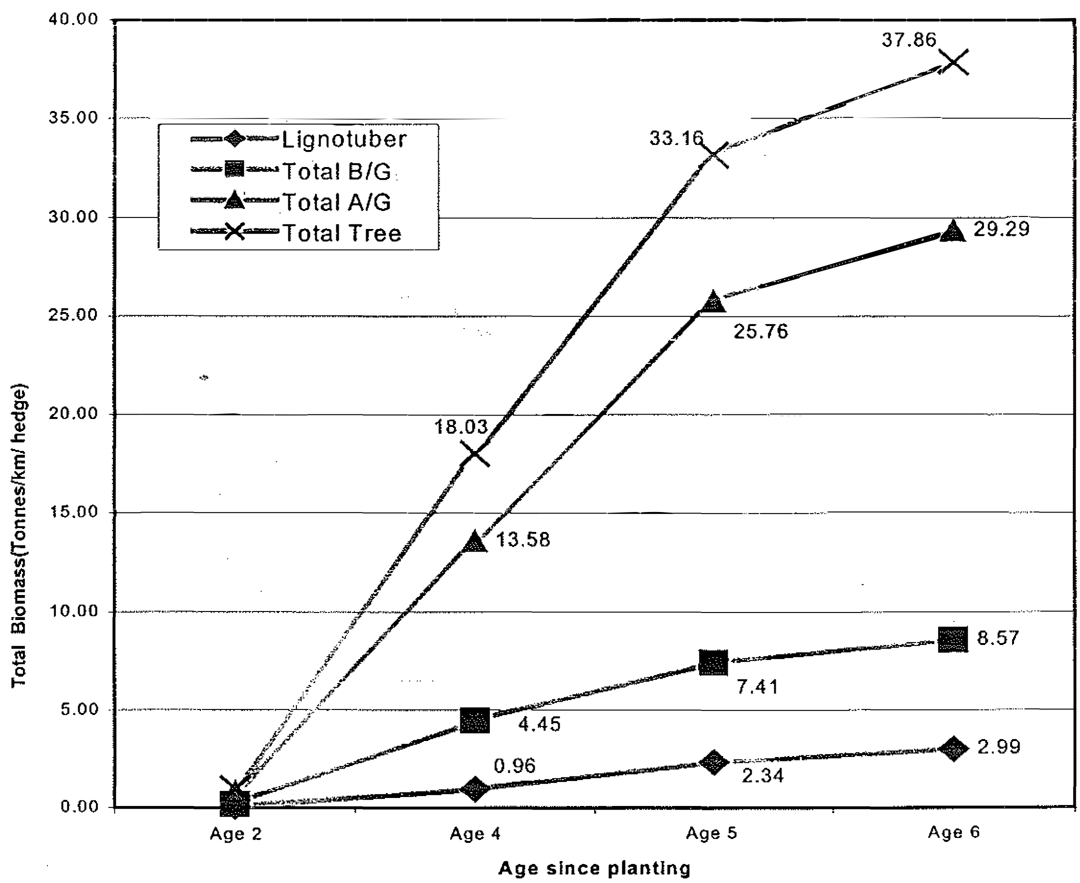


Figure 5.1 Total mean biomass per kilometre of hedge for *E. plenissima* at different ages with various tree components.

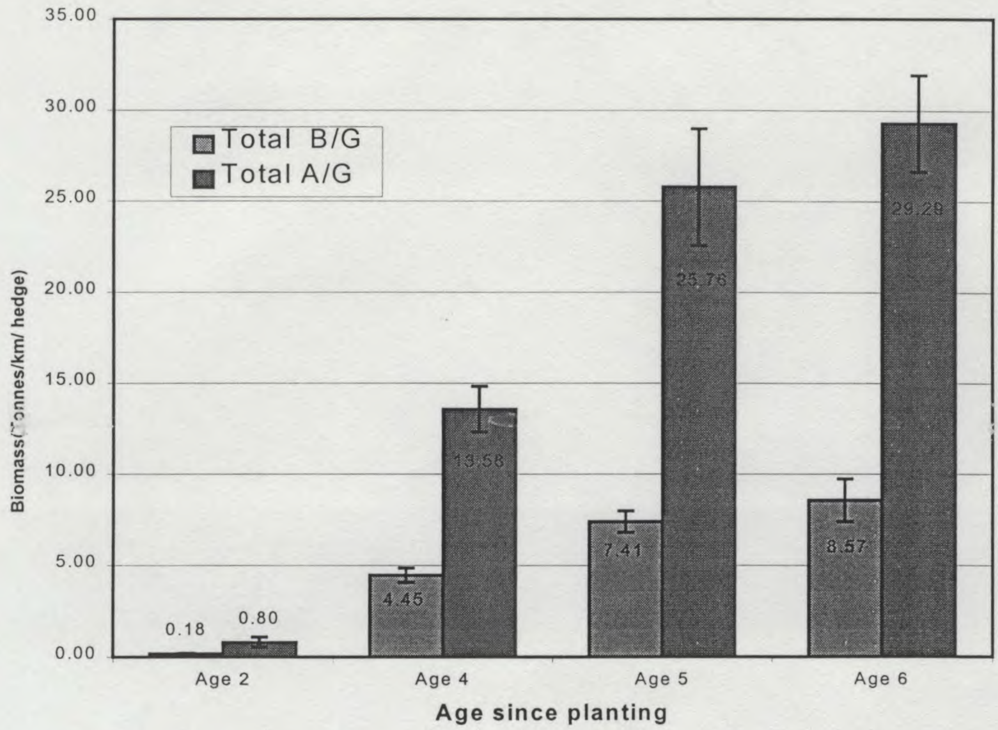


Figure 5.2 Total above-ground (A/G) and below-ground (B/G) biomass per kilometre of hedge for *E. plenissima* at different ages with standard error.

Figure 5.3 Percentage below-ground and above-ground of the total tree biomass for E. *plenissima*.

The total above-ground biomass compared to below-ground biomass is displayed within Figure 5.2. At age six 29.29 tonnes per kilometre of hedge of above-ground biomass was recorded. This represented 77.37 % of the total tree biomass (Figure 5.3). At age two 81.65% of biomass was within the above ground components and 18.35% within the below ground organs. The relationship changes for trees aged four with 75.3% within the above-ground components and 24.69% within below-ground component. For ages five and six the relationship was not significantly different (P=. 422) with above ground growth being around 77% of the total biomass. The general trend over the four ages was that ratio of below-ground biomass to above- ground biomass increases from age two to four and then plateaus after age four.

The total biomass and the percentage that this represents of above-ground biomass for the three tree components are presented within Figure 5.4. These results illustrate a very clear trend that with age the amount and percentage that this represents of above-ground biomass of stem material increases significantly. Conversely the percentage that leaf represents of total biomass is steadily decreasing with age. The total leaf biomass continues to increase up until age five but decreases at age six.

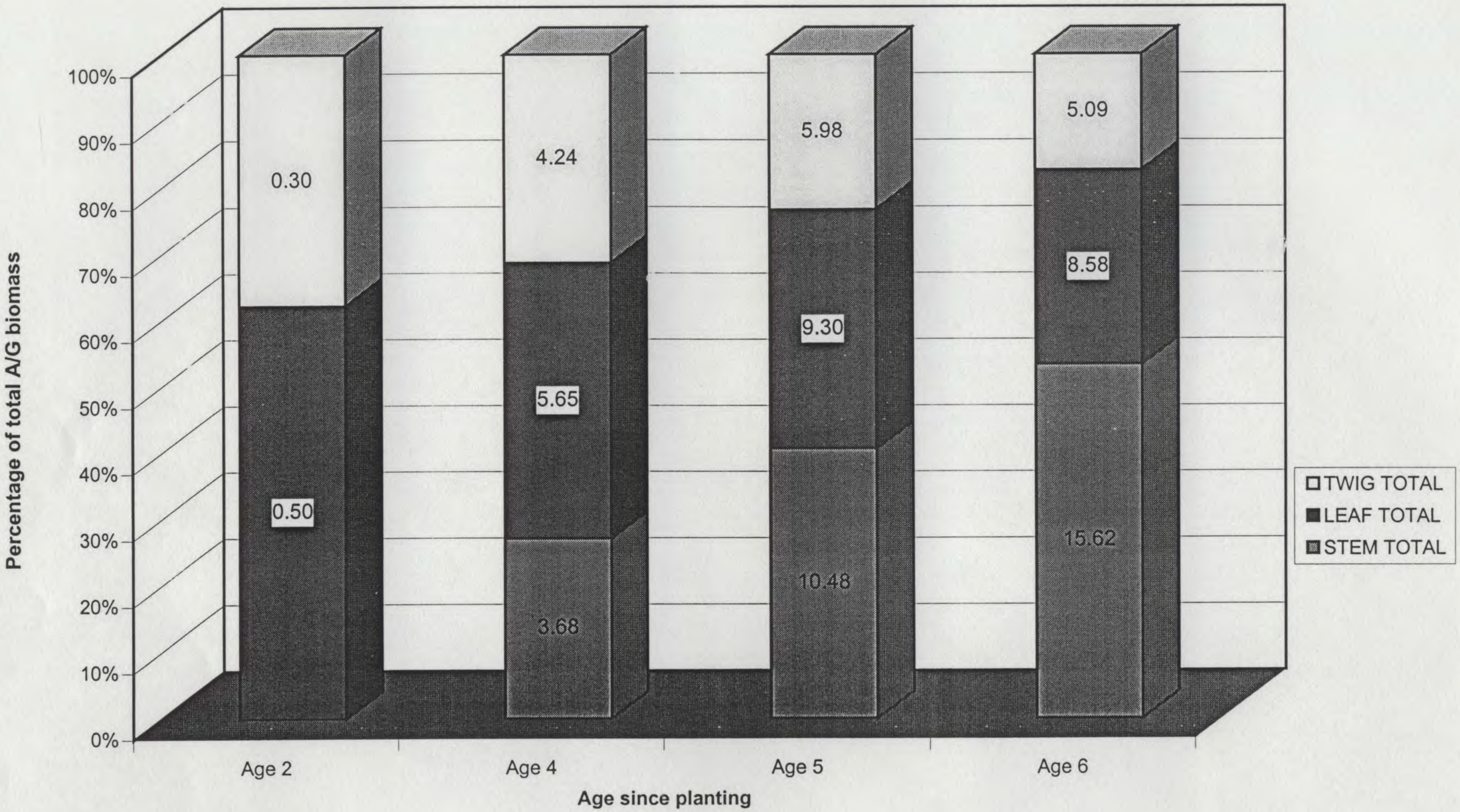


Figure 5.4 Mean biomass (numbers within categories) and percentage of above ground biomass that different tree components represent for various ages of *E. plenissima*

5.2.2 E. lissophloia

The total biomass of *E. lissophloia* between age four and five was not significantly different (P=0.224) with age five recording 25.99 tonnes per kilometre of hedge compared to 23.60 tonnes for age four. The above-ground biomass was smaller on average for age five trees than trees aged four years (14.85 & 16.45 tonnes/km/hedge) but this difference was not significant (P=0.765).

The relationship between above ground and below-ground biomass is represented with Figure 5.6. Trees aged four years recorded 30.31 % below-ground and 69.69% above–ground biomass of total biomass respectively The difference between above and below–ground biomass was significant (P=0.410) The average lignotuber represents 11.05% of the total biomass. Within trees aged five years the relationship changed with the below-ground biomass representing a greater proportion of the total biomass (42.87%). The lignotuber represents 18.78% of the total tree biomass.

The total leaf biomass of trees aged five (3.78 tonnes/km hedge) accounted for 24.45% of the total above-ground biomass and was smaller than four year old trees (5.19 tonnes /km hedge) which accounted for 34.95% but this difference was not significant (p=0.248) The total woody material (twigs+stems) was 11.25 and 11.06 tonnes per kilometre of hedge for age four and five respectively. This represents 64.05%(four years) and 75.55%(five years) of the total tree biomass respectively.

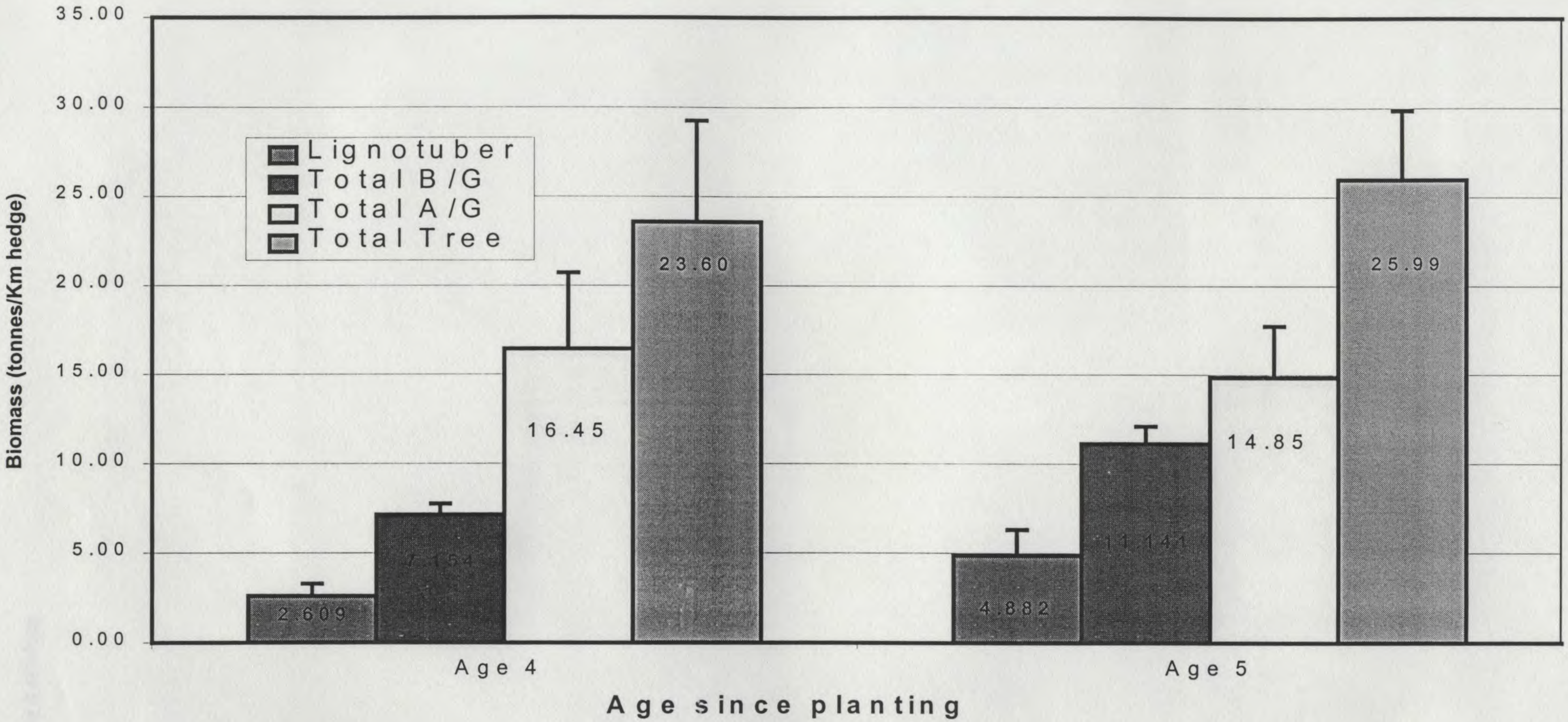


Figure 5.5 Total tree biomass for *E. lissophloia* at ages four and five after planting with standard error

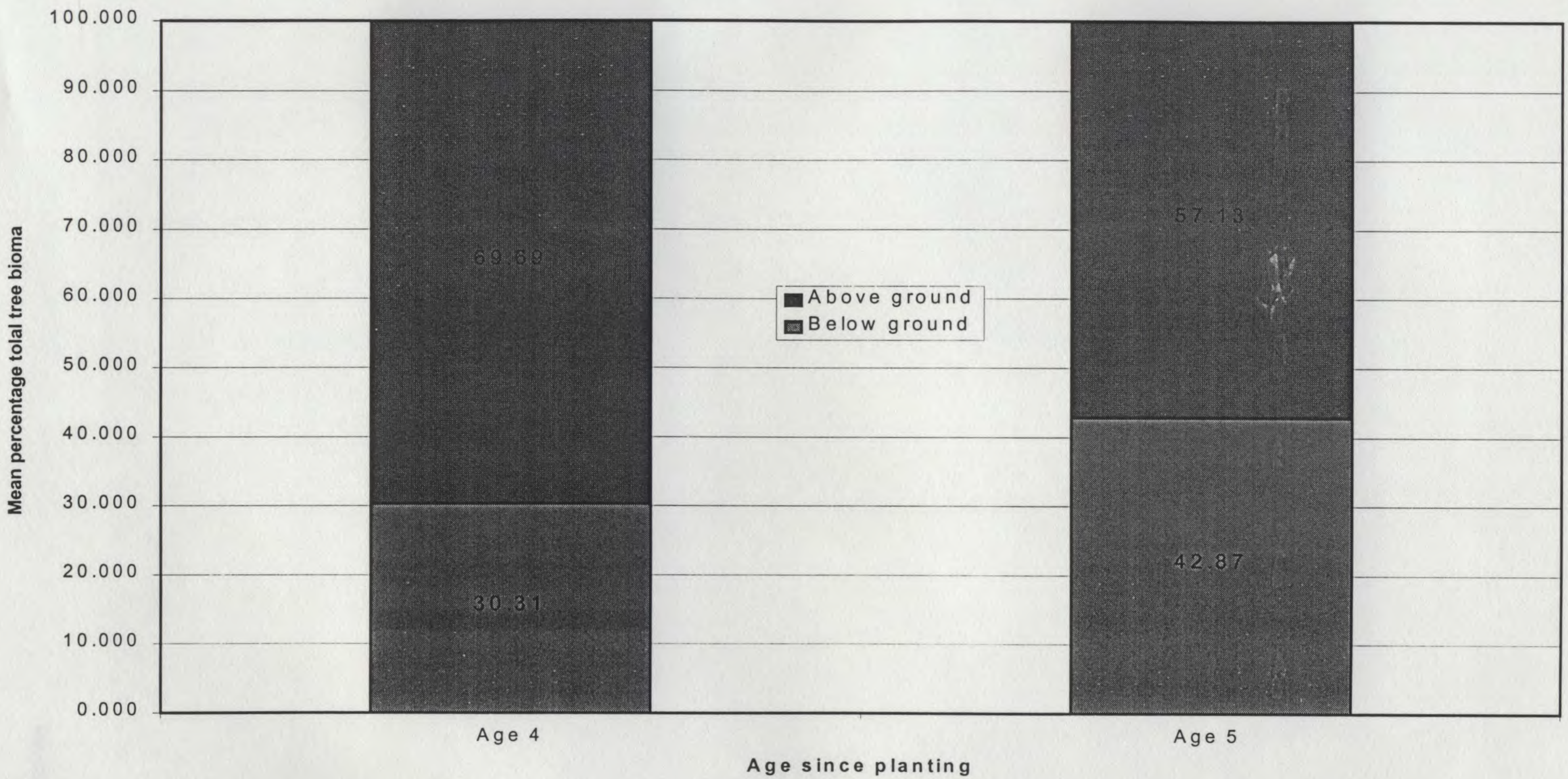


Figure 5.6 Percentage of total tree that above-ground (A/G) and below-ground biomass represents at ages four and five for *E. lissophloia* .

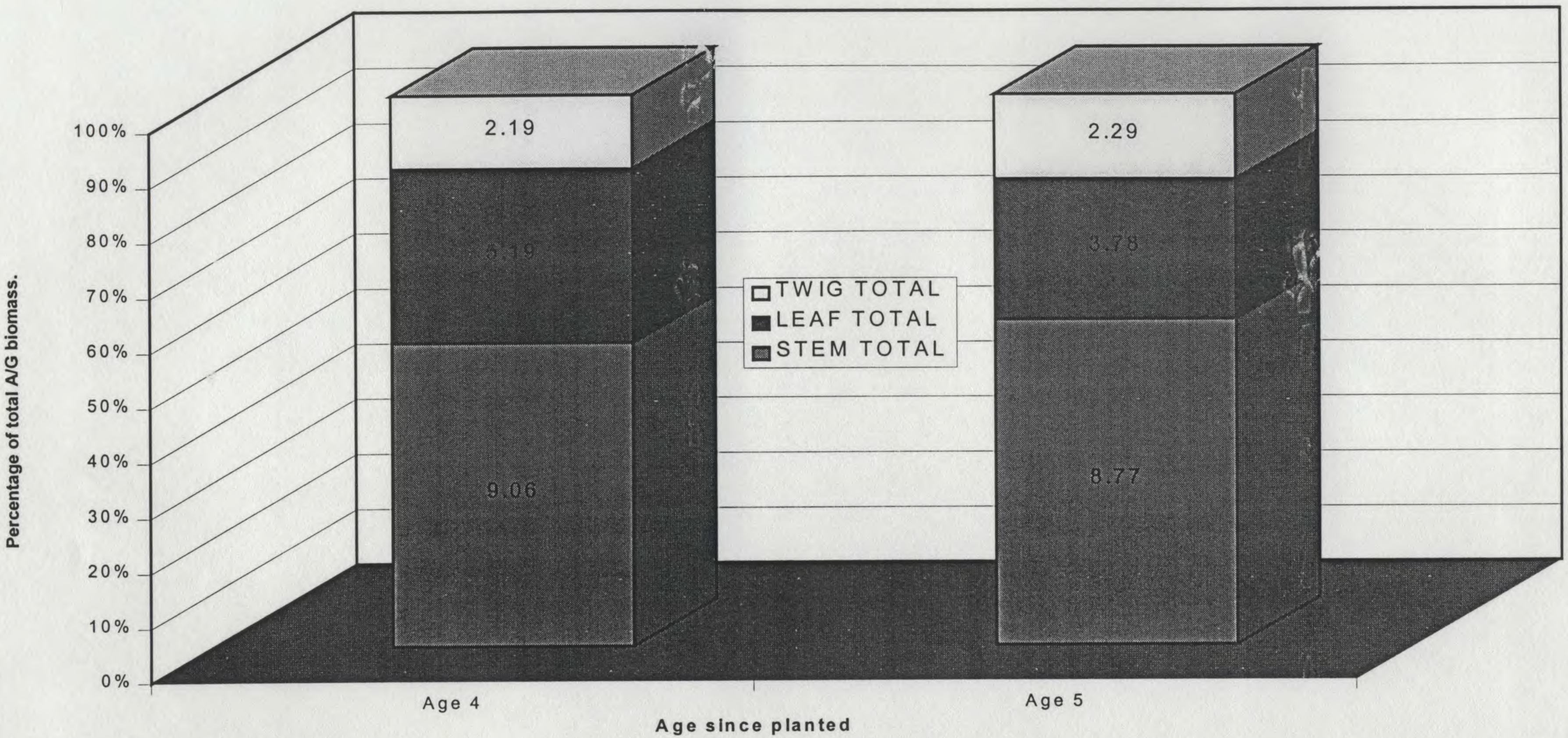


Figure 5.7 Mean biomass (numbers within categories) and percentage of above ground biomass that different tree components represent for various ages of *E. lissophloia.*

5.2.3 E. plenissima and *E. lissophloia*

E. lissophloia recorded on average larger total, above and below-ground and lignotuber biomass (tonnes/km hedge) at ages four and five compared to *E. plenissima* An exception to this trend was mean total leaf biomass (Figure 5.8). *E. plenissima* displayed 9.89 and 12.36 tonnes per kilometre of hedge for ages four and five compared to *E. lissophloia* recorded 8.41 and 5.92 tonnes per kilometre of hedge respectively. At age five this represents a significant difference (P<0.05) of more than twice the total leaf biomass.

E. plenissima displayed a significant difference between ages five and six (P<0.05) with the mean leaf biomass being 3.84 tonnes per kilometre of hedge less than age five.

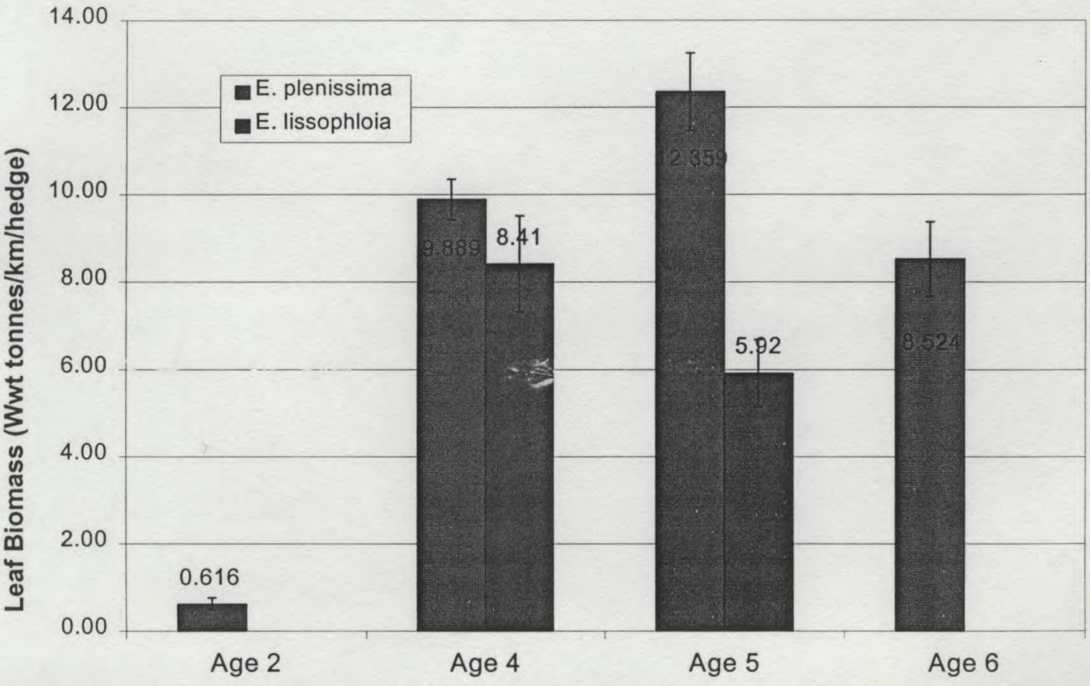


Figure 5.8 Mean leaf biomass (Fresh wt tonnes/km hedge) for *E. lissophloia* and *E. plenissima* at various ages with standard error.

5.3 Discussion

The general trend over the four ages for *E. plenissima* was that ratio of below-ground biomass to above- ground biomass increases from age two to four and then plateaus after age four.

The total biomass and the percentage that this represents of above-ground biomass for the three tree components are presented within Figure 5.4. These results illustrate a very clear trend that with age, the total amount of stem material and the percentage of the total above-ground biomass that this represents increases significantly. Conversely the percentage that leaf represents of total biomass is steadily decreasing with age. The total leaf biomass continues to increase up until age five but decreases at age six. This indicates that with time *E. plenissima* is changing the amount of energy apportioned to the growth of various tree components. It appears that stem growth accelerates at the expense of leaf biomass. To manage for leaf production the first harvest should be at age five. A harvest at age 5 would also maximise total below-ground biomass, and coincide with the critical lignotuber biomass determined within chapter 4

The relationship between above and below-ground biomass changed significantly between age 4 and age five for *E. lissophloia*. Below-ground biomass represents 42.87% of the total biomass at age four compared to 30.31% at age five. This would indicate that below-ground production is receiving an increased portion of photosynthetic products. Lambers (1987) found that around half of all photosynthates are exported from the leaves to the below-ground structures. Given the relationship between above and below-ground found within this study, *E. lissophloia* uses 2.3 times the photosynthates to produce 1 kilogram of below-ground biomass compared to above-ground biomass at age four. For *E. plenissima* this relationship is 3.1 times the photosynthates to produce one kilogram of below-ground biomass compared to above-ground biomass. To maximise the total leaf (fresh weight kg/tree) and therefore the total oil, the first harvest should be at age four and five respectively for *E. lissophloia* and *E. plenissima*.

While the results of this study represent new information about "oil mallee" growth patterns, there are limitations placed on the results by the methods used. The below-ground biomass data is most likely an under representation of the actual standing biomass. The methods used were the easiest and fastest way to as accurately as possible estimate below-ground biomass. Future research should try to sample at a much greater depth as this would gather most of the remaining roots. Perhaps the biggest limitation and this applies to all aims was the lack of site replication. It was only possible to sample one site per age classes. For stronger statistical analysis 3 replications with 10 individuals would be more accurate and would eleviate any in-situ differences. The results from Age 6 may have been an underestimate because of the planting formation being block design. There would have been greater competition for water resources with the larger stocking density.

CHAPTER 6

6 HARVESTED VERSUS NON-HARVESTED BIOMASS SEQUESTRATION

6.1 INTRODUCTION

The preceding chapters have dealt with standing biomass of the two study species with the aim of determining how much biomass is permanently retained within an "oil mallee" system. Chapter five determined the relationship between the below and above ground components and established the total biomass pool. These results do not take into consideration one of the primary reasons for planting "oil mallees", which is the potential for an economic return by harvesting the oil contained within the leaves. To date there has not been a commercial harvest of "oil mallees" in Western Australia but once the cost of harvesting and distillation have been reduced large scale harvesting will commence (W. O'Sullivan, pers comm. 1998). Wildy (1996) studied 6-month re-coppice growth for trees aged 2.5 years when harvested. He found that at Kalannie on deep sands, both *E. plenissima* and *E. lissophloia* had over 85% survival of trees but the standing above-ground harvest of *E. lissophloia* was double that of *E. plenissima*. However this study made no assessment of the impact harvesting has on the below ground organs.

It is has been established within this thesis (Chapter 4) that lignotuber growth plateaus at age five for *E. plenissima*. It was concluded that this was an adaptive response by the mallee eucalypts to periodic removal of their above-ground biomass by fire. Having established a large enough store of starch reserves within the lignotuber at age five, the tree can divert productivity from storage, to root expansion and above-ground growth. The question can then be asked what will the plant response be to the removal of above-ground biomass. Specifically what will be the response to the depletion of starch reserves and how does the above-growth respond to the use of those reserves?

It is hypothesised that harvesting the above-ground biomass will not have an effect on the size of the lignotuber and below-ground total biomass. It is proposed that after the initial recovery of the above-ground biomass, particularly leaf area, the tree will divert productivity towards the recovery of used carbon stores in the event of another disturbance.

There are a number of assumptions that were made in determining harvesting changes on biomass sequestration. Firstly, it was assumed that the standing biomass of the unharvested and harvested trees was the same at age 2.5 years, when the harvested trees initially had the above-ground biomass removed. This assumption allows differences between trees to be apportioned to the harvesting rather than differences that may have been existing at the time of initial harvest. The less than 10% variation found in the amount of above and below-ground growth of unharvested 5 year old trees for both study species supports this assumption (Refer to Chapter 4). However, ideally a number of trees should have been measured at age 2.5 years for both above and below-ground biomass. Wildy (1996) measured the above-ground biomass but only a site average is available for the two study species. This highlights the problem with the static nature of this design. Continuous sampling of trees on a six month basis would be more accurate in evaluating change in biomass sequestration. Although changes may be substantial over 2.5 years this says nothing for changes that may have occurred within that time.

Only one soil type was assessed. It could be that species soil preference may effect the ability of a species to re-coppice and utilise below-ground reserves. Ideally a number of soil types could have been studied to assess changes associated with soil type preferences.

Given these limitations the specific aim of this chapter is to determine the effect of harvesting the above-ground biomass at age 2.5 years has on the biomass sequestration of below-ground organs of *E. plenissima* and *E. lissophloia* on deep yellow sands.

6.2 RESULTS

6.2.1 E. lissophloia.

The below-ground biomass of *E. lissophloia* does not support the hypothesis that harvesting will have no effect on below-ground biomass sequestration. Both lignotuber biomass and total below-ground biomass of the harvested treatment are significantly different ($P<0.05$ & $P<0.05$, respectively) to the unharvested trees (Figure 6.1). The lignotuber biomass is on average 2.90 tonnes per kilometre of hedge less than the unharvested trees. The total below-ground biomass is 11.14 tonnes per kilometre of hedge for the unharvested trees compared to 3.64 tonnes per kilometre of hedge for the harvested *E. lissophloia.*

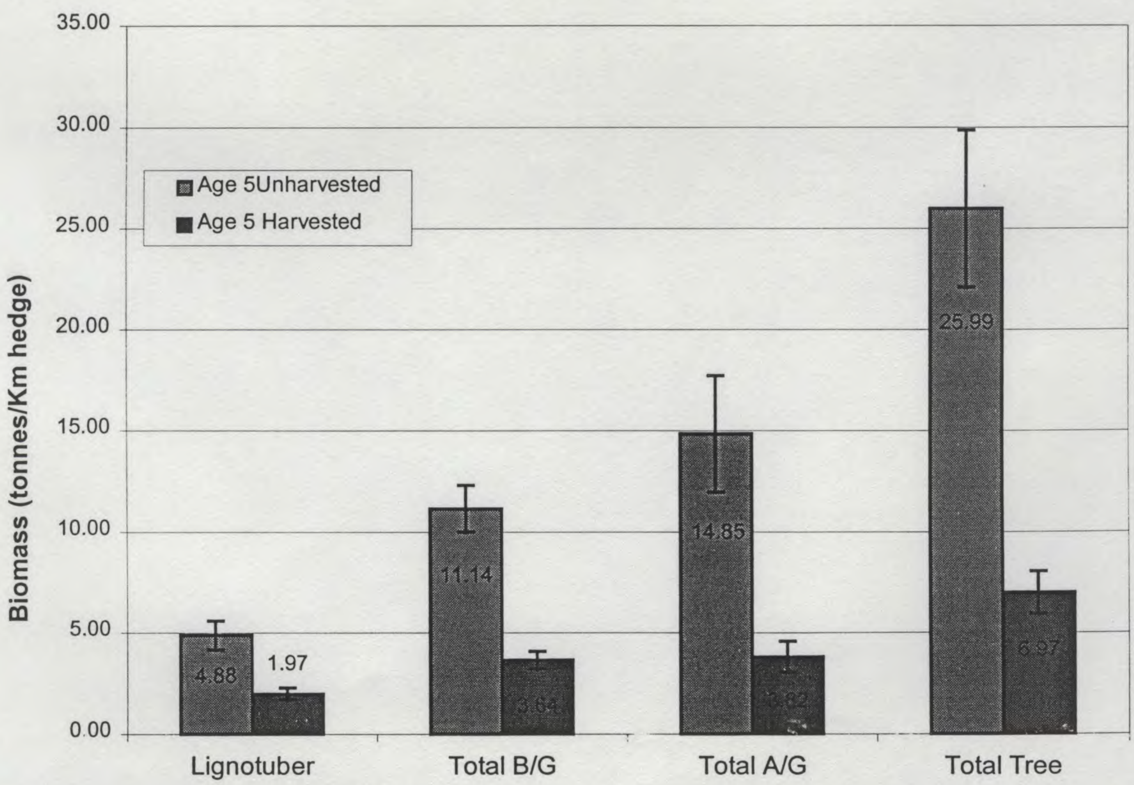


Figure 6.1 Harvested versus unharvested mean biomass (tonnes per kilometre of hedge) of ***E. lissophloia*** for the lignotuber, total below-ground (B/G), total above-ground (A/G) and total tree with standard error.

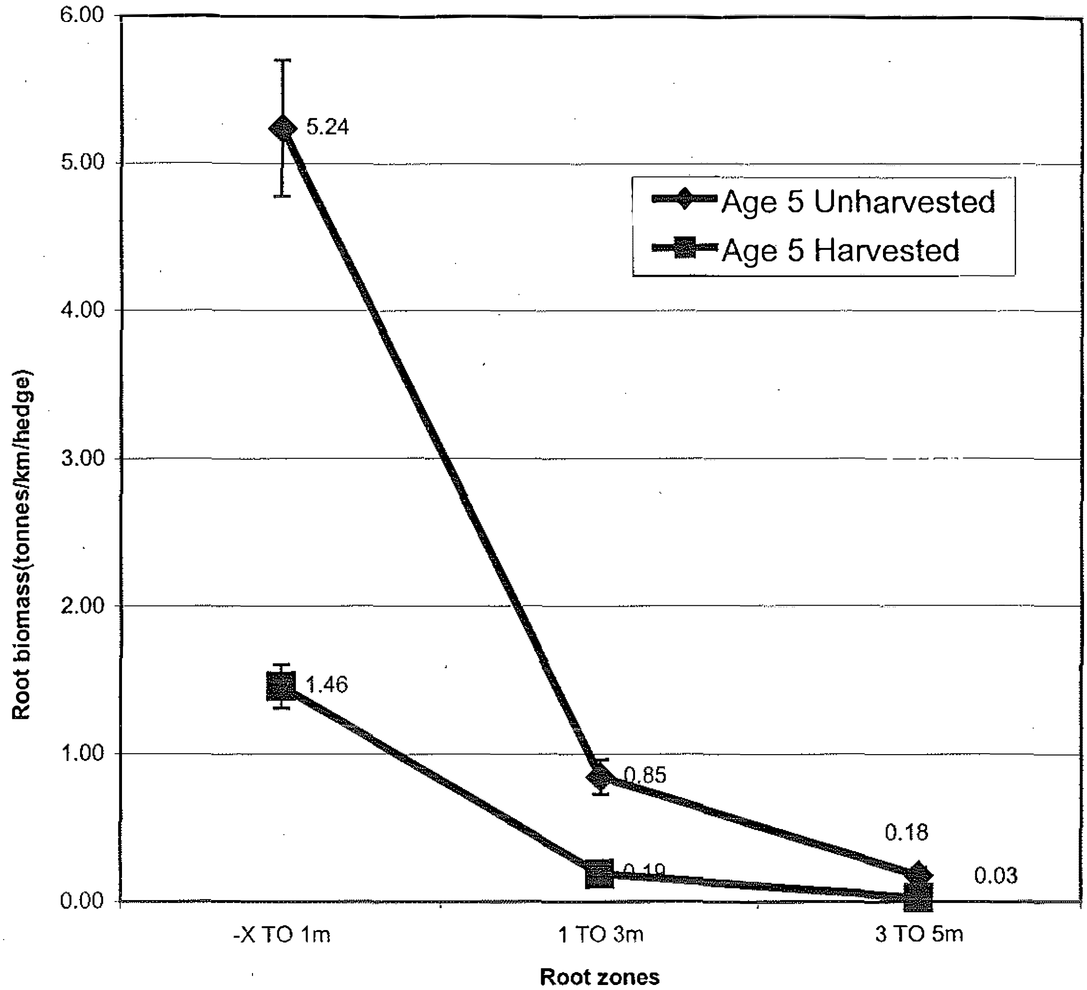


Figure 6.2 Unharvested versus harvested distribution of root biomass (without lignotuber) for *E. lissophloia* from the centre of the alley, with standard error.

The distribution of roots between unharvested and harvested trees is significantly different for all three root zones (Figure 6.2). There is 3.5 times the root biomass within the zone around the tree ($P<0.05$); 2.1 times within the 1-3 metre zone (p=0.001) and 6 times more within the 3-5 metre zone (p=0.036) respectively. Harvesting has reduced the root biomass within the cropping zone (1-5metres) by 240%.

Of the total root biomass (without the lignotuber) each zone is 83.6% (x-1m), 13.5% (1-3m) and 2.9% (3-5m) respectively for the unharvested trees. The ratio for the harvested trees is 77.2% (x-1m), 21.2% (1-3m) and 1.6% (3-5m) respectively.

Table 6.1 Percentage of the total below-ground biomass of *E. lissophloia* that the lignotuber and total roots represent for unharvested and harvested trees respectively.

	Unharvest	Harvested
Total roots	56.2%	45.9%
Lignotuber	43.8%	54.1%

The proportion that the lignotuber and total roots represent of the total below-ground biomass for the two variables is represented in Table 6.1. The roots of the unharvested trees account for 56.2% and the lignotuber 43.8% of total below-ground biomass respectively. This ratio is reversed for harvested trees with 45.9% of total below-ground biomass being root and 54.1 % being lignotuber biomass.

An important aspect of harvesting is the leaf biomass of subsequent re-growth (Table 6.2). For *E. lissophloia* total leaf biomass for the harvested trees is 3.03 tonnes per kilometre of hedge. This is significantly less ($P<0.05$) than the unharvested leaf biomass which was 7.09 tonnes per kilometre of hedge. This result does not factor in the leaf biomass of the initial harvest. By including a site average (data from Wildy, (1996)) of the leaf biomass for *E. lissophloia* at age 2.5 years the total harvested leaf biomass increases to 7.85 tonnes per kilometre of hedge.

Table 6.2 Total leaf biomass (Fresh weight/ tonnes/km hedge) of *E. lissophloia* for unharvested and harvested trees.

	Unharvested	Harvested
Total leaf biomass.	7.09	3.03
Standard error.	1.58	0.54
Total 5-year leaf biomass.	7.09	7.85[A]

[A] Includes site average data for 2.5 year old *E. lissophloia* from Wildy (1996).

6.2.2 *E. plenissima*

In contrast to *E. lissophloia, E. plenissima* displayed no significant difference in the size of the lignotuber or total below-ground biomass ($p=0.315$ & $p=0.594$ respectively) (Figure 6.3). The lignotuber of *E. plenissima*, on average (3.20 tonnes per kilometre of hedge) was larger in size over the 5 years of growth for the harvested trees compared to the unharvested trees (2.34 tonnes per kilometre of hedge). The unharvested trees recorded slightly higher below-ground biomass (7.41 tonnes/km hedge) than the harvested trees (6.46 tonnes/km hedge).

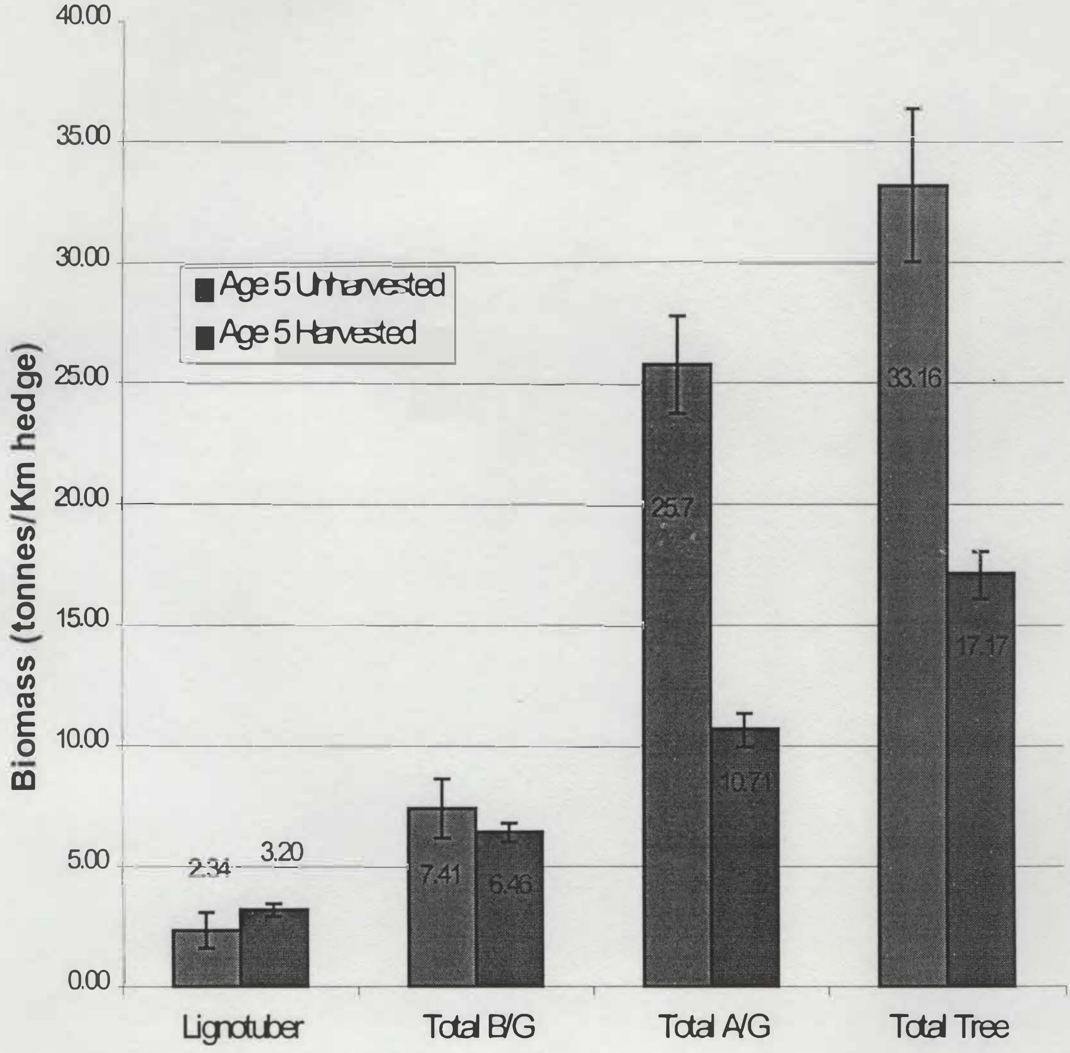


Figure 6.3 Harvested versus unharvested biomass (tonnes per kilometre of hedge) of *E. plenissima* for the lignotuber, total below-ground (B/G), total above-ground (A/G) and total tree with standard error.

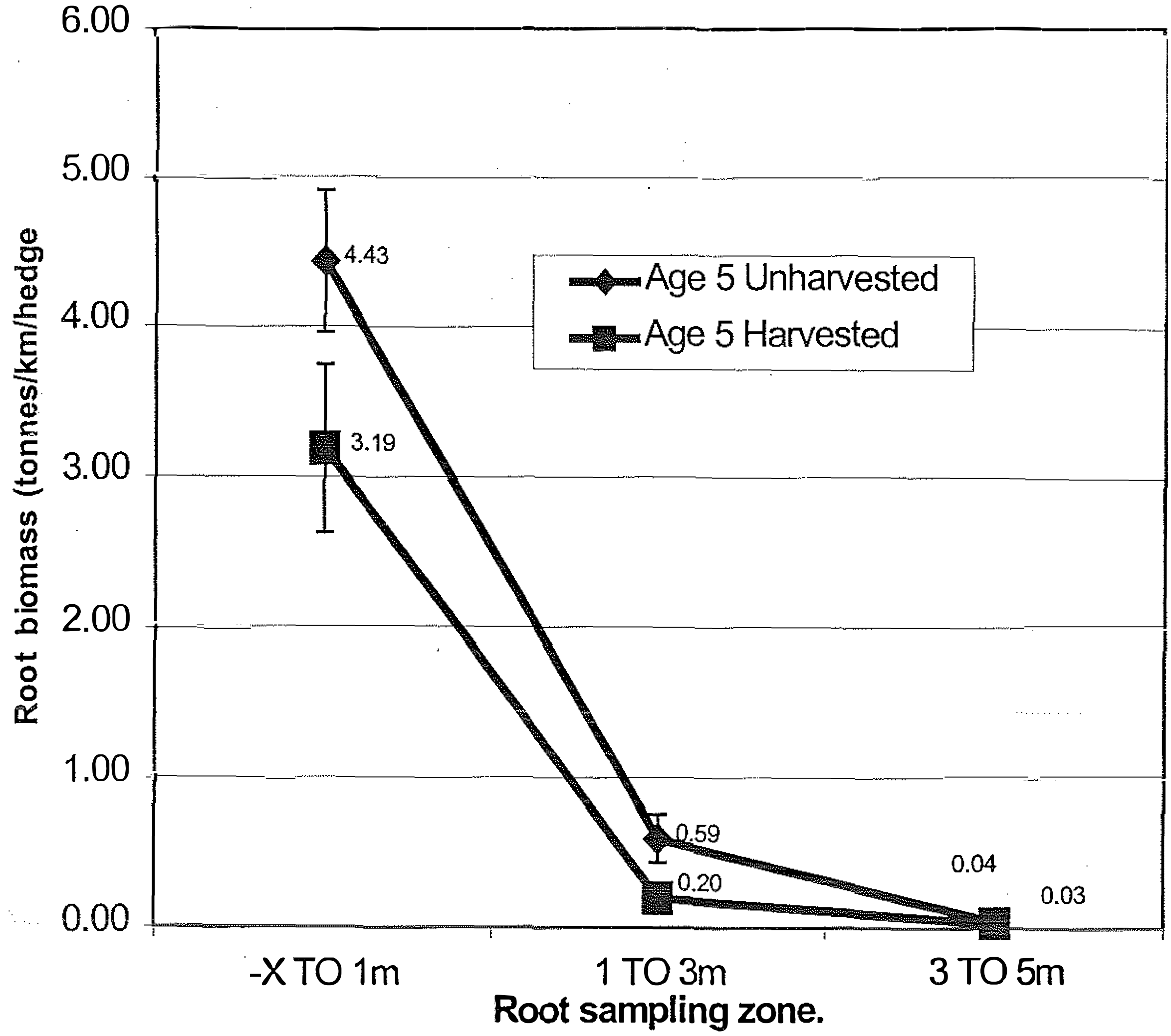


Figure 6.4 Unharvested versus harvested distribution of root biomass (without lignotuber) for *E. plenissima* from the centre of the alley, with standard error.

Within each root sampling zone unharvested trees recorded higher root biomass than the harvested trees but this was not a significant difference (X-1m, p=0.128; 1-3m, p=. 066; 3-5m, p=. 498) (Figure 6.4). The total amount of root biomass that was within the cropping zone (1-5m) was smaller for harvested trees by 0.43 tonnes per kilometre of hedge compared to unharvested trees.

Table 6.3 Percentage of the total below-ground biomass of *E. plenissima* that the lignotuber and total roots represent for unharvested and harvested trees respectively.

	Unharvested	Harvested
Total roots	68.4 %	52.8%
Lignotuber	31.6%	47.2%

The proportion that the lignotuber and total roots represent of the total below-ground biomass for the two variables is represented in Table 6.3. The roots of the unharvested trees account for 68.4% and the lignotuber 31.6% of total below-ground biomass respectively. This contrasts with a near 50-50 ratio for the harvested trees.

An important aspect of harvesting is the leaf biomass of subsequent re-growth (Table 6.4). For *E. plenissima* total leaf biomass for the harvested trees is 3.03 tonnes per kilometre of hedge. This is significantly less ($P<0.05$) than the unharvested leaf biomass, which was 16.77 tonnes per kilometre of hedge. This result does not factor in the leaf biomass of the initial harvest. By including a site average (data from Wildy, (1996)) of the leaf biomass for *E. lissophloia* at age 2.5 years the total harvested leaf biomass increases to 11.62 tonnes per kilometre of hedge.

Table 6.4 Total leaf biomass (Fresh weight/ tonnes/km hedge) of *E. plenissima* for unharvested and harvested trees.

	Unharvested	Harvested
Total leaf biomass.	16.77	7.25
Standard error.	1.93	1.93
Total 5-year leaf biomass.	16.77	11.62[A]

[A] Includes site average data for 2.5 year old *E. lissophloia* from Wildy (1996).

6.2.3 E. plenissima and E. lissophloia.

The differences between the 2 species at age 5 for unharvested trees have been explored within chapter five.

Table 6.5 Comparison of harvested biomass(tonnes/km hedge) categories for *E. plenissima* and *E. lissophloia* with significance.

Tonnes/km hedge.	Lignotuber	Total B/G Biomass	X-1m Roots	1-3m Roots	3-5m roots	Total A/G Biomass	Total leaf
E. plenissima	3.20	6.46	3.19	0.20	0.03	10.71	7.25
E.lissophloia	1.97	3.64	1.46	0.19	0.03	3.82	3.03
P value	0.189	0.084	0.063	0.90	0.92	0.023*	0.025*

^ leaf biomass is fresh weight (tonne/km hedge)
*denotes significant difference.

Over the range of categories *E. plenissima* recorded higher biomass than *E. lissophloia* but only the above ground components were significantly different. *E. plenissima* had 2.5 times more above-ground biomass and over double the leaf biomass than *E. lissophloia.*

6.3 Discussion.

E. plenissima and *E. lissophloia* present two contrasting stories about the effects harvesting has on biomass sequestration. *E. plenissima* displayed no significant difference between unharvested and harvested trees for lignotuber biomass. Annual yearly re-growth of the above ground biomass for the harvested trees was 4.28 tonnes per hectare per year and unharvested trees recorded only slightly higher average annual growth (5.15 tonnes/km hedge). At age 2.5 years *E. plenissima* has enough carbon reserves within the lignotuber to fund rapid re-growth after harvesting and establish a leaf area that is large enough to restock the lignotuber and maintain above ground growth.

Harvesting resulted in the ratio of below-ground to above-ground biomass changing to incorporate more below-ground biomass and most of this increase was utilised by the lignotuber. This confirms that harvesting causes *E. plenissima* trees to respond so as to be adequately prepared for another harvest event.

The leaf area is 75 % of the total above ground growth. This equates to 7.25 tonnes of leaf (fresh weight, tonnes/km/hedge). The average oil concentration for *E. plenissima* is 3 % and converts to 218 kilograms of oil per kilometre of hedge. This is significantly higher than was first predicted for coppice harvest (Bartle *et al.*, 1996).

The distribution of the root system has contracted towards the centre of the alley. Harvesting has reduced the amount of root biomass within the cropping zone. The process of root formation is dynamic with roots being dropped off as available nutrients and water are utilised (Dickmann & Pregitzer, 1992). Harvesting causes a reduction in external root biomass so as to reduce the respiration cost involved with the transport of soil water and nutrients (Dickmann & Pregitzer, 1992). This enables greater resources to be partitioned to lignotuber and coppice growth.

Harvesting has caused some major changes in growth characteristics for *E. lissophloia*. There was a significant difference between unharvested and harvested trees for all growth characteristics. Harvested lignotuber size was more than half that of unharvested trees. Harvesting has prompted *E. lissophloia* to utilise reserves within the lignotuber. The size of these reserves at the time of harvesting was most probably not large enough to sustain vigorous coppice growth. This may be the result of a number of factors. *E. lissophloia* is usually found on red loams. The growth of below-ground structures was most probable limited by a reduced level of available soil nutrients and water that is characteristic of deep yellow sands (Bell, 1991).

6.3.1 Management implications.

These findings have important implications for the management of *E. plenissima*. Firstly it is important to note the limitations of this study. Because the results of the first harvest were unavailable it was assumed that unharvested trees and harvested trees had the same biomass. This may not have been the case and may be the cause of the *E. lissophloia* reduced harvested biomass. Because this was a one off sampling period no assessment can be made of the changes between harvesting period. There may not have been any reduction in the lignotuber size for *E. plenissima*. Dickmann & Pregitzer (1992) argue that disturbance/harvesting of the above-ground components reduces lignotuber carbon reserves and limits short-term growth but this can not be proven conclusively. Even with this shortcoming this study still provides a useful snap shot at a static harvesting response of the two study species.

The results from chapter four indicate that lignotuber biomass accumulation plateaus at age five. It was suggested that this would be the minimum length of time required to allow for the adequate sequestration of below-ground carbon. However the results of this chapter indicate that *E. plenissima* has adequate below-ground biomass at age 2.5 to fund coppice re growth and maintain below-ground biomass. Managers of "oil mallee" plantations now have a wider choice of harvesting times. Plantings are currently distributed over a wide geographical range and it is likely for economic reasons planting areas will be harvested at one time. Site combinations over 2.5 years can be harvested without effecting the next harvest yield.

For *E. lissophloia* this study indicates that the first harvest should not be at age 2.5 years. Soil type was noted as the most probable cause of the reduced biomass growth. However the results of the unharvested trees indicate that a later harvest time would be appropriate. *E. lissophloia* recorded significantly higher below-ground growth at ages four and five compared to *E. plenissima.* Due to lack of older sites it was not possible to determine when biomass growth plateaus for *E. lissophloia.* Harvesting after age five should enable *E. lissophloia* to maintain its below-ground biomass and therefore adequately fund future above-ground growth.

CHAPTER 7

7 SYNTHESIS, CARBON CREDITS AND "OIL MALLEES"

7.1 INTRODUCTION

Currently there is an evaluation of the total carbon pools for the three major agroforestry (this project is one of those evaluations) systems within Western Australia. The purpose of this evaluation is to establish the potential to offset carbon emissions through re-vegetation. Oil mallees have a significant potential for this is due to the permanent nature of their root systems, particularly the lignotuber.

Accounting procedures are still being finalised for the calculation of carbon credits. The basic equation within a forest takes 50.0% of the standing biomass as carbon. Carbon that is fixed over a long period of time can be traded, the current price is around $AUS16 (Shea *et al.*, 1998).

The purpose of this chapter is to synthesis the findings all the of chapters four, five and six into an understanding of how the biomass data recorded relates to the total carbon contained within the standing biomass of existing stands, particularly the permanent below-ground carbon and the wood (twig +stem).

7.2 SYNTHESIS

In addressing aim1 it was concluded that the annual rate of growth recorded for below-ground biomass and lignotuber biomass of *E. plenissima* was maximised at age five. These results indicate that age five is the critical point of biomass sequestration. Growth of below-ground structures will continue once critical point of storage is reached. By modeling the annual increase recorded for lignotuber biomass between age five and six over 100 years, assuming that this is constant over that time a hedge planted with *E.*

plenissima an estimation of the potential total carbon that is sequested can be attained will contain 34 tonnes of lignotuber carbon per kilometre of hedge. This is equivalent to 28.0 kilograms of carbon per tree. This indicates that there will be large stores of permanent carbon within an "oil mallee" system. This could potentially provide the farmer with $5.44 per kilometre per year of hedge over the life time of the hedge. Most farms within the district have around 400 kilometres of hedge. This provides a small supplemental income which aids in the promotion of land use diversification, which is one of the major principles of sustainable agriculture (Roberts, 1995).

The static nature of sampling technique prevents definite conclusions from being drawn for the data. Growth is continuous within plants and examining biomass with one off harvesting events of different age trees will not give an accurate account of biomass sequestration. However given these limitations it is still a reasonable conclusion that at age five *E. plenissima* has reached a critical level in the size of the lignotuber and any harvest event after this time will not affect the ability of *E. plenissima* re-coppice and maintain and increase the size of the below ground lignotuber which will maximise the benefits a landholder will get from carbon credits.

In assessing the effects harvesting had on biomass production it was found *E. plenissima* displayed no significant difference between unharvested and harvested trees for lignotuber biomass. At age 2.5 years *E. plenissima* has enough carbon reserves within the lignotuber to fund rapid re-growth after harvesting and establish a leaf area that is large enough to restock the lignotuber and maintain above ground growth. Harvesting therefore has no signific̮ant on the amount of carbon credits that *E. plenissima* can potentially attract.

These findings have important implications for the management of *E. plenissima.* firstly it is important to note the limitations of this study. Because the results of the first harvest were unavailable it was assumed that unharvested trees and harvested trees had the same biomass. This may not have been the case and may be the cause of the *E. lissophloia's* reduced harvested biomass. Because this was a one off sampling period no assessment can be made of the changes between harvesting period. There may not have been any reduction in the lignotuber size for *E. plenissima*. The literature states that harvesting reduces lignotuber carbon reserves and limits short term growth but this can not be proven conclusively. Even with this short-coming this study still provides a useful snap shot at a static harvesting response of the two study species (Dickmann & Pregitzer, 1992).

Harvesting has caused some major changes in growth characteristics for *E. lissophloia*. There was a significant difference between unharvested and harvested trees for all growth characteristics. Harvested trees had a lignotuber size that was half that of unharvested trees. Harvesting has prompted *E. lissophloia* to utilise reserves within the lignotuber. If the maximisation of carbon credits is the goal of "oil mallee" plantings it is suggested that *E. lissophloia* not be harvested until a much older age.

The benefits that oil mallees have in terms of greenhouse gas reduction extend beyond their ability to fix large amounts of carbon within their lignotubers. The use of fossil fuels in the agricultural landscape for harvesting, goods transport will be reduced because harvesting of "oil mallees" will be on a 2 year rotation and the first harvest will not be until age fives. If "oil mallees" are planted over 15% of the landscape this will significantly reduce greenhouse gas emissions.

E. plenissima and *E. lissophloia* displayed different growth characteristics but both have the potential to provide substantial benefits to the agricultural landscape in terms of carbon retention in the soil, greenhouse gas sinks and a diversification of farming income and practice.

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9 Appendix One.

Table 9.1 Site soil characteristics

		Age 2 "Cail"	Age 4 "I. Stanley"	Age 5 "D. Stanley"	Age 6 "Rolinson"
Topsoil texture	Sand	Sand	Sand	Sand	Sand
Topsoil colour	Munsell	7.5YR6/4D	7.5YR5/3M	7.5YR6/4D	7.5YR6/4D
Topsoil Depth	m	0 – 0.16m	0- 0.22m	0-0.12m	0- 0.27m
Topsoil conductivity	dS/m	0.058	0.0285	0.0422	0.0742
Topsoil pH	$CaCl_2$	4.45	4.33	4.55	4.28
Topsoil P	mg/kg	17.0	18.5	8.0	19.0
Topsoil K	mg/kg	55.0	51.5	60.0	23.5
Topsoil N*	mg/kg	4	4	17	2
Topsoil OC	%	1.01	0.985	0.895	0.56
Subsoil texture	Sand	Sand	Sand	Sand	Sand
Subsoil colour	Munsell	10YR7/6D	10YR6/6D	10YR6/8M	10YR6/8M
Subsoil Depth	m	0.16-1.0m	0.22-1.0m	0.12-1.0m	0.27-1.0m
Subsoil conductivity	mS/m	0.0363	0.0351	0.0504	0.0365
Subsoil pH	$CaCl_2$	4.01	4.03	3.92	4.18
Subsoil P	mg/kg	2	1.5	1.5	2.5
Subsoil K	mg/kg	20	19.5	23	23.5
Subsoil N	mg/kg	1	1.5	16.5	1
Subsoil OC	%	0.15	0.13	0.15	0.19
Topsoil moisture	score	3	2	4	3

Denotes significant difference between sites($P<0.05$*).

Table 9.2. Mean percentage of total carbon within different tree components for *E. plenissima* and *E. lissophloia*

	Age	Leaf	Stem	Roots x-1m	Roots 3-5m	Lignotuber
E. plenissima	2.00	85.57	93.35	87.09	83.63	89.7
	4.00	89.11	91.21	83.72	90.47	97.29
	5.00	89.73	90.89	89.45	89.51	90.20
	5.00harv	93.19	95.79	93.74	93.65	87.72
	6.00	89.27	88.07	88.12	89.63	88.79
E. lissophloia	4.00	89.73	86.56	92.85	91.43	88.08
	5.00	88.26	88.35	94.3	94.88	83.41
	5.00harv	91.87	89.63	93.24	82.23	83.22